An Expanded Study of Shielded Metal Arc Welding Electrode Performance in Fusion Welding

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Abstract

Research was performed into the SMAW performance characteristics of several electrodes under various polarity conditions. Electrode types investigated included EXX10, E7016, and E7018 and they were tested under three polarity conditions DC negative, square wave AC and DC positive. The electrode performance was evaluated according to deposition efficiency and the weld bead dimensions of crown height, weld penetration, and bead width.

The investigation determined that using square wave AC rather than conventional sinusoidal AC improved the performance of electrodes not designed for AC; however, it did not completely stabilize the arc to the point that the weld would be similar to a weld produced from a DC power source.

The results conclude that no one electrode of the four EXX10 series provided AC results comparable to those obtained using a DC source across all properties tested. If an operator wishes to use an EXX10 electrode for an AC application the electrode will have to be selected according to specific desired properties such as penetration depth or crown height.

Investigation into the effects of iron in the flux of E7018 electrodes were compared against similar electrode coating compositions without iron, E7016. It was determined that the iron in the flux, when combined with a short arc length, provided superior deposition efficiency but changes the weld bead profile increasing the crown height and decreasing the bead width. The short arc condition is conducive to metal transfer via electrode shorting of the welding circuit. The shorting mechanism accelerates electrode melting and increases metal transfer. The trends are apparent for both the E7018 and E7016 electrodes, however, they are more pronounced for the E7018 due to the additional iron in the electrode coating.

INTRODUCTION

Shielded metal arc welding (SMAW), as a welding technique, is relatively inexpensive, readily mobile and very versatile, making it one of the most prolific welding processes used for construction and repair of mild steel structures, particularly in the upstream petroleum industry. The process utilizes the heat from an electric arc to bring the metal in the piece to be joined and the consumable electrode to the molten state across what is referred to as the welding circuit.

The primary components of the process is an electrical circuit comprised of a power source with one terminal connected to the workpiece by a grounding cable and a second terminal connected to the electrode. The arc is produced when the electrode gets close enough to the workpiece that, under sufficient voltage, the air gap breaks down and ionizes.

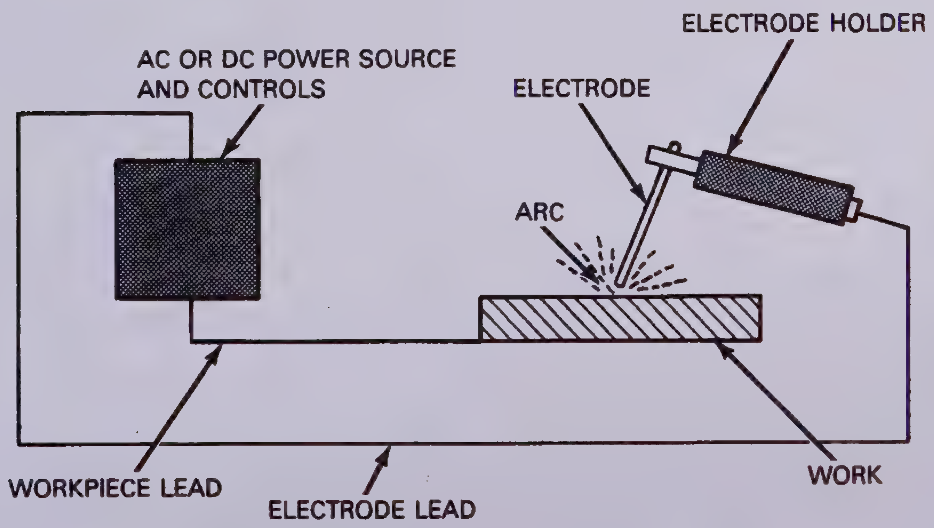


FIGURE 1. – Elements of a typical welding circuit for SMAW

Once the arc is struck sufficient current and voltage must be maintained to keep the arc stable. Sufficient current is required to keep the electrode from developing a sustained metal bridge to the workpiece, shorting out the welding circuit. Sufficient voltage is required to reignite the arc should it be extinguished. The power requirements for SMAW are non-linear and complex, however, they fall into two general categories of direct and alternating current.

Direct current (DC) can be applied to the system in two polarities, electrode negative and electrode positive (also referred to straight and reversed polarity, respectively). In the electrode negative configuration electrons are drawn off the electrode, and in electrode positive, electrons are transferred from the workpiece to the electrode. The stability of the arc is sensitive to electron emissivity at the cathode with heat transfer being greatest in the direction of electron flow. A SMAW configuration utilizing a poor electron emitter at the cathode (carbon steel base metal using electrode positive DC polarity) would be expected to produce an unstable arc with a less than optimal deposition rate.

Alternating current (AC) provides an alternative that has two advantages over DC, the power source is cheaper and the alternating polarity prevents welding current induced arc blow. Traditional AC sources develop sinusoidal voltage profiles that extinguish and reinitiate the arc with every cycle. For convention 60 Hz power sources the reversal time is 8333 microseconds. Problems when welding using AC are typically encountered during reignition, as illustrated in Figure 2 on the next page. During the voltage cycle there exists an extinction region between the voltage at which the arc is extinguished (d.) and the voltage at which the arc is reignited (f.). The

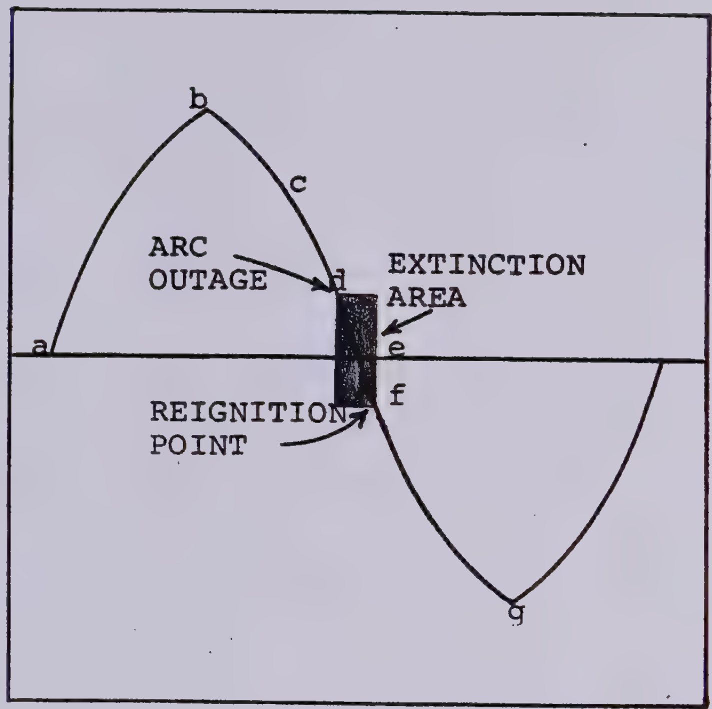


FIGURE 2. – Conventional alternating current sinusoidal voltage profile.

longer the arc is extinguished the more time the arc area has to cool and the higher the voltage required to reignite the arc. In the worst cases the arc has cooled to the point where it will have to be reinitiated manually by the operator.

Electrodes designed for use in AC conditions have coatings modified to assist reignition. Electrode coatings for AC and DC applications perform one or more of the following functions: [1]

1. provides a gas shield to shield and protect the molten filler metal from atmospheric contamination as it passes across the arc.
2. provides scavengers, deoxidizers, and fluxing agents to keep the weld metal clean and to prevent excessive grain growth in the weld metal.
3. establishes the electrical characteristics of the electrode.

4. provides a slag blanket to protect the hot weld metal from the air and to enhance the properties and shape of the weld bead.
5. provides a way to add additional alloy elements to enhance the properties of the weld.

Electrodes designed for SMAW under AC condition contain auxiliary ignition elements that assist in arc reignition. Elements used to enhance arc reignition have low ionization potentials, such as sodium and potassium (with ionization potentials of 5.14 and 4.34 volts, respectively) that enable easier reestablishment of the arc (compared with iron at 7.83 V). [2]

Experimental work conducted during this investigation focused on three electrode types, EXX10, EXX16 and EXX18. EXX10 electrodes are cellulosic electrodes that are designed for deep penetration and multipass welding where good mechanical properties are desired and radiographic inspection is used. EXX16 electrodes are designed for low hydrogen applications that require welds of exceptional physical properties and x-ray quality. This electrode is designed for difficult to weld materials and has been designed for AC and DC applications. EXX18 electrodes are similar in composition to the EXX16, however, they contain 30% iron powder that produces a higher deposition rate, improved weld appearance, better slag removal and higher usable current.[3] EXX18 are not regarded as good performers when using AC[4] due, in part, to increased slag volume and larger weld pools.

Electrodes without auxiliary ignition elements such as EXX10 would not be expected to perform very well under conventional AC welding conditions. Electrodes with the additions, such as EXX16 and EXX18, would be expected to produce results superior to EXX10 when welded under the same AC

Classification	Current and Polarity	Welding Positions	Type of Covering	Penetration	Surface Appearance	Slag
EXX10	DC reverse polarity (electrode positive)	All	High-cellulose sodium	Deep	Flat, wavy	Thin
EXX11	AC or DC, reverse polarity	All	High-cellulose potassium	Deep	Flat, wavy	Thin
EXX12	AC or DC, straight polarity (electrode negative)	All	High-titania sodium	Medium	Convex, rippled	Heavy
EXX13	AC or DC, straight polarity	All	High-titania potassium	Shallow	Flat or concave, slight ripple	Medium
EXX14	DC, either polarity or AC	All	Iron powder-titania	Medium	Flat, slightly convex, smooth ripple	Easily Removed
EXX15	DC, reverse polarity	All	Low hydrogen sodium	Medium	Flat, wavy	Medium
EXX16	AC or DC, reverse polarity	All	Low hydrogen potassium	Medium	Flat, wavy	Medium
EXX18	AC or DC, reverse polarity	All	Iron powder low hydrogen	Shallow	Flat, smooth, fine ripple	Medium
EXX20	DC, straight polarity or AC for H-fillets; DC, either polarity or AC for flat welds	H-fillets and flat	High Iron Oxide	Medium	Flat or concave, smooth	Heavy
EXX24	DC, either polarity or AC	H-fillets and flat	Iron powder-titania	Shallow	Slightly convex, very smooth, fine ripple	Heavy
EXX27	DC, straight polarity or AC for H-fillets; DC either polarity or AC for flat welds	H-fillets and flat	Iron powder iron oxide	Medium	Flat to slightly concave, smooth, fine ripple	Heavy
EXX28	AC or DC, reverse polarity	H-fillets and flat	Iron powder low hydrogen	Shallow	Flat, smooth, fine ripple	Medium

FIGURE 3. – Operating Characteristics of Mild Steel and Low-Alloy Steel Electrodes

conditions. The operating characteristics of common mild steel and low-alloy electrodes are displayed in Figure 3.

An alternative to the addition of auxiliary ignition elements is modifying the AC profile to minimize the arc extinction time and to maximize the time the current and voltage spend at their maximum values. The desired profile is achieved by utilizing a semi-square AC power source. The profile is achieved by amplifying the sine wave and chopping off the peaks. The resulting profile is illustrated below in Figure 4.

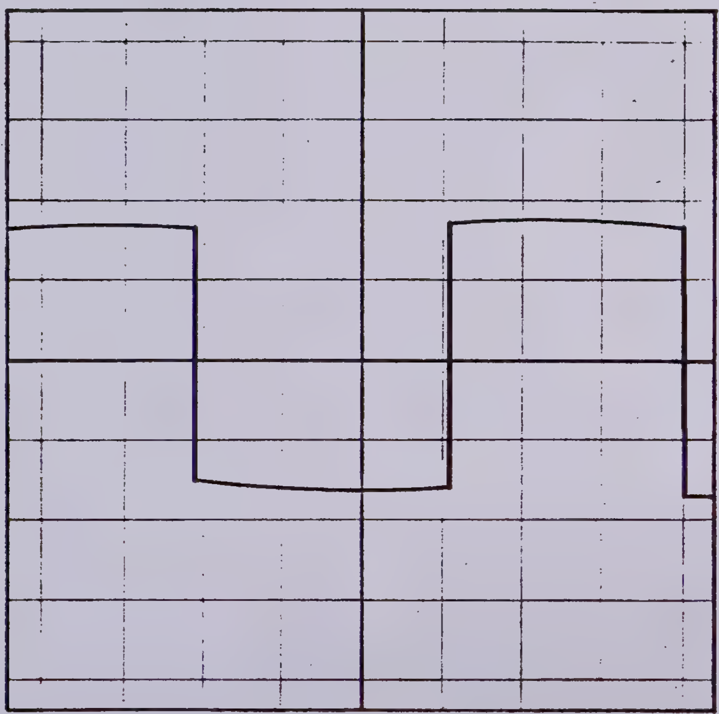


FIGURE 4. – Square Wave Alternating Current Voltage Profile.

The square wave illustrated is produced by the Miller Syncrowave, 300 Ampere AC/DC power source used for this investigation. The polarity

transition is extremely rapid when compared to the conventional AC voltage profile. The transition time is between 80 to 150 microseconds[5] considerably faster than the 8333 microsecond transition time required for a conventional AC power source. The shorter transition time would be expected to provide less time for the arc to cool and better performance for electrodes not designed for AC welding (i.e.: EXX10).

Electron transfer occurs in arc welding under both AC and DC conditions. For all arc-welding processes, most electron transfer occurs through electron generation at the cathode through thermionic and field emission. Thermionic emission occurs when a cathode composed of a refractory material (carbon or a metal with a sufficiently high melting and boiling point (ex: W, Ta, Mo)) is heated to a temperature sufficient to emit electrons, with a current density J, according to the Richard-Dushman equation:[6]

$$J = AT^2 e^{-b/T}$$

A = 6.5 x 10^5 A/m^2K^2; a constant for most metals.

T = surface temperature in Kelvin.

$b = \dfrac{\phi e}{k}$; where e = 1.60 x 10^{-19} C; charge on an electron.

k = 1.38 x 10^{-23} J/K; Boltzmann's constant.

ϕ = (thermionic) work function (J).

These materials are referred to as thermionic emitters and form arcs easily with current emitted over a relatively large area.

Non-thermionic emitters (such as carbon steel) cover the majority of materials that are commonly welded and transfer electrons primarily through field emission. Field emission is developed in high electric fields and tends to occur at small, extremely mobile sites that follow areas that have slightly lower emission requirements, such as oxide particles. The current density, *J*, is largely dependant on the electric field, *E*, and the work function, ϕ, according to the Fowler-Nordheim equation:[7]

$$J = \frac{6\times10^{-6}\cdot\left[\mu/\phi\right]}{\mu+\phi}E^2 e^{\left(\frac{-6.8\times10^9\cdot\phi^{3/2}}{E}\right)}$$

μ = Fermi energy for the cathode material.

ϕ = (thermionic) work function (J).

The localized and mobile emission sites produce highly localized current density with correspondingly strong irregular forces that may adversely effect metal transfer.

Direct current provides a steadier arc and smoother metal transfer than alternating current, due primarily to the fact that the polarity is not constantly changing as it does with AC. Most covered electrodes operate best when the polarity is electrode positive (reverse polarity), even though electrodes can be designed for electrode negative (straight polarity). Electrode positive provides deeper penetration for the welding process, however, electrode negative develops higher electrode melting rates.[8]

One serious problem commonly encountered when welding magnetic materials (primarily iron and nickel alloys) with DC is arc blow. Arc blow is due to residual magnetism or magnetic field asymmetries developed in the area to be welded. [9] Prior handling or processing techniques, such as lifting using electromagnets or previous welding, can induce residual magnetism. Magnetic field asymmetries can be produced a number of ways. Frequent cases include ground locations, edge effects, mass distribution (example: welding sections of differing thicknesses), and heterogeneity in the electrical properties of the materials to be welded.[10] The asymmetric magnetic fields developed cause problems by deflecting the arc during the welding process. The deflection causes excessive spatter in the direction of the arc blow, increased electrode consumption, and can result in incomplete fusion preventing production of a satisfactory weld.

Common remedies recommended for reducing arc blow include: [11]

1. Place worklead connections as far as possible from the joints to be welded.
2. If back blow is the problem, place the workpiece connection at the start of the welding, and weld toward a heavy tack weld.
3. If forward blow causes trouble, place the workpiece connection at the end of the joint to be welded.
4. Position the electrode so that the arc force counteracts the arc blow.
5. Use the shortest possible arc consistent with good welding practice. This helps the arc force to counteract the arc blow.
6. Reduce the welding current.
7. Weld toward a heavy tack or runoff tab.
8. Use the backstep sequence of welding.
9. Change to AC, which may require a change in electrode classification.

10. Wrap the worklead around the workpiece in a direction such that the magnetic field it sets up will counteract the magnetic field causing the arc blow.

Many of the remedies suggested can be difficult to implement in field applications such as repair and field welding. Ground lead locations can be restricted by the physical location of fixed or partially buried facilities (example: pipelines), demagnetizing equipment may not be available and electrodes rated for AC use may not be available or appropriate for the application. The most promising solution, particularly for field applications, would be to utilize a modified AC current that would allow the operator to utilize electrodes designed for DC, without the inherent problems with arc stability and reignition.

Summary

The focus of this investigation is to investigate the performance of EXX10, EXX16 and EXX18 electrodes under all polarity conditions AC, DC electrode positive and DC electrode negative. Square wave AC is going to be utilized rather than convention sinusoidal AC to determine if electrodes not designed for AC can provide performance comparable to electrodes designed for AC. EXX16 and EXX18 electrodes are designed for AC; however, EXX18 is not regarded as a good performer[12] with AC. EXX10 electrodes are very common and widely used, however, they are specifically not designed for AC use.

Performance will be evaluated according to deposition efficiency and bead shape to determine if acceptable results can be developed using polarities other than what the electrodes are rated for. The bead shape will be evaluated according to crown height, weld penetration and bead width and deposition efficiency will be assessed by calculating normalized melting and disposition rates. Once the electrodes have been tested and assessed the data will be evaluated to determine which electrodes offer the most application flexibility and, most importantly, which electrodes can be used with square wave AC, when necessary, to counter the effects of arc blow.

Experimental Procedure

Equipment used for the experiment was a Miller Syncrowave, 300 Ampere AC/DC power source. The tests were run at AC and DC straight and reverse polarity. The volt-ampere curve and the duty cycle of the machine are illustrated below in Figure 5.

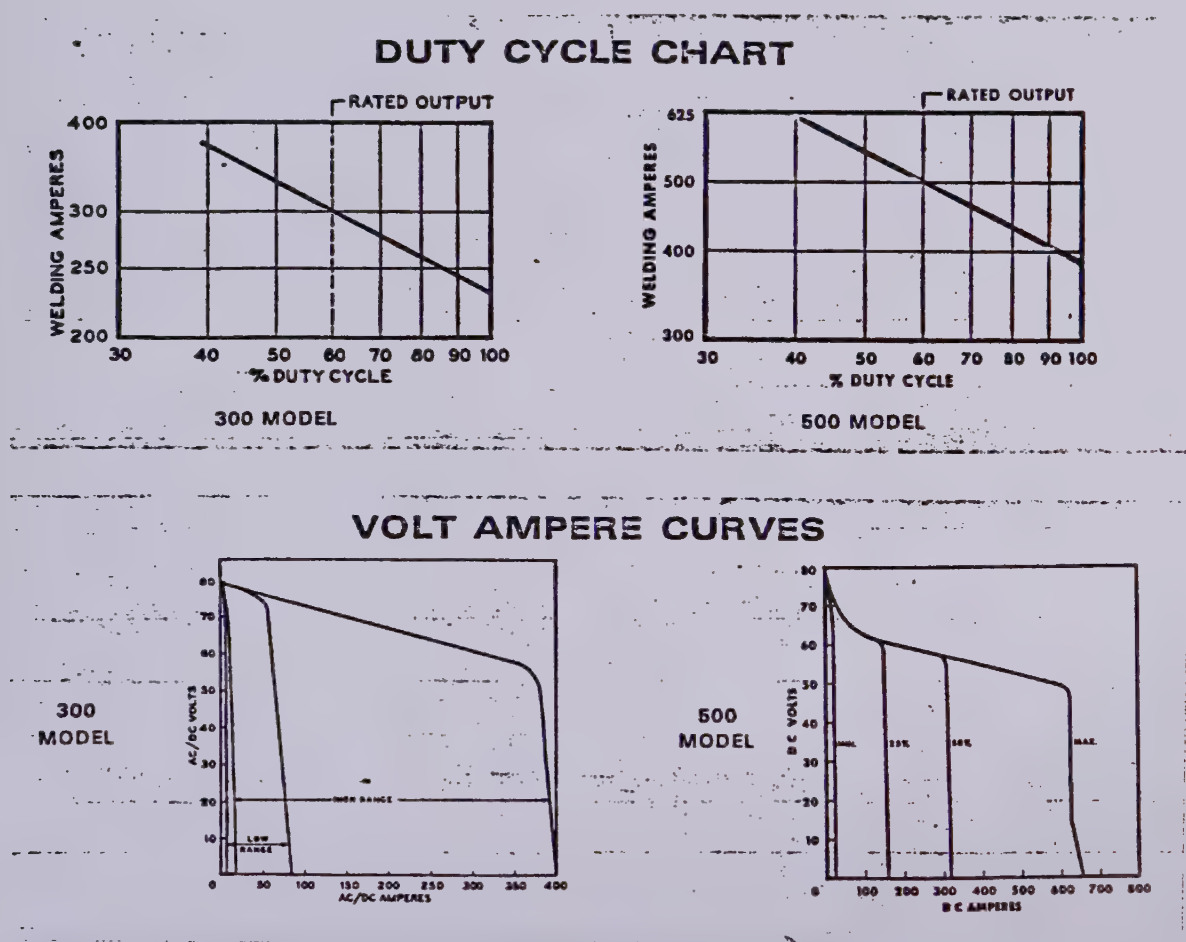


Figure 5. – Duty Cycle Chart and Volt-Ampere Curve of the Miller Syncrowave 300.

A number of welding rods were used for the experiment. The electrodes included E6010-5P, E6010-5P+, CSA E6010 LA ULTRA 10, CLA E6010X, FRX E7016-1Ni, and E7018-1+. The 6010 electrodes were stored at room temperature and the 7016 and 7018 electrodes were stored in an oven at 120°C.

Experimental welds were deposited on flat and channel sections of A36 steel. Macrostructural analysis was performed on weld beads deposited on flat bar sections and weld performance was evaluated from welds performed on angle sections. The welds were deposited under three polarity conditions, DC straight, AC and DC reversed. Additional parameters tested included long and short arc conditions for the 7016 and 7018 electrodes.

Macrostructure Analysis

For macrostructure analysis, single beads were deposited on sections of flat bar (measuring 4″ x 10″ x 0.25″) at each polarity. The electrodes were burnt off at a constant speed of 200 mm/second. The speed was set by adjusting a rheostat control box that controlled the speed of a moving bed upon which the welding was performed. Sections, perpendicular to the weld, were taken 1.5″ from the start and end of each weld. Areas of the section unaffected by the welding process were removed and the remaining weld area was mounted, polished to 600 grit SiC and etched with a 10% nital solution. Digital photographs were taken of all macrostructures and the images were analyzed using a software package to measure weld area, crown height, penetration depth, and weld width. Average values were calculated for each electrode and polarity between values from the weld start and the weld end. A mounted section example is illustrated, on the next page, in Figure 6.

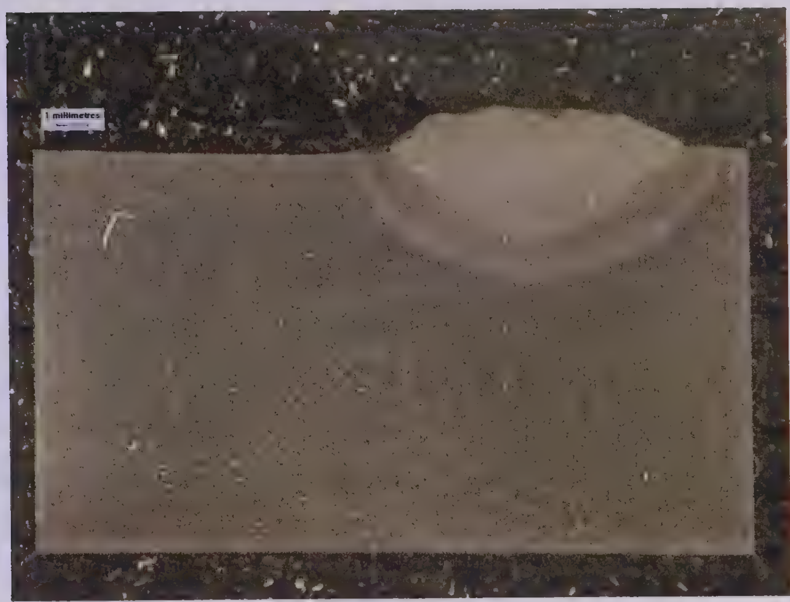


FIGURE 6. – Macrostructure of E6010-5P+ electrode on AC, 1.5″ from the end of the weld.

Electrode Performance

Weld performance was assessed for each electrode and polarity setting by depositing three beads on a section of angle iron. Each electrode was used for approximately one minute and the base plate was cooled in water between runs. The base plate (section of angle iron) and the electrodes were weighed before and after all welding was completed for amount of weld metal consumed and deposited. The electrode lengths were measured before and after welding to assess the length of electrode consumed. Current, voltage and time were also recorded for each weld run.

Calculations were performed from average weld times, lengths consumed, currents and voltages. Burnoff rates were calculated from the averages of

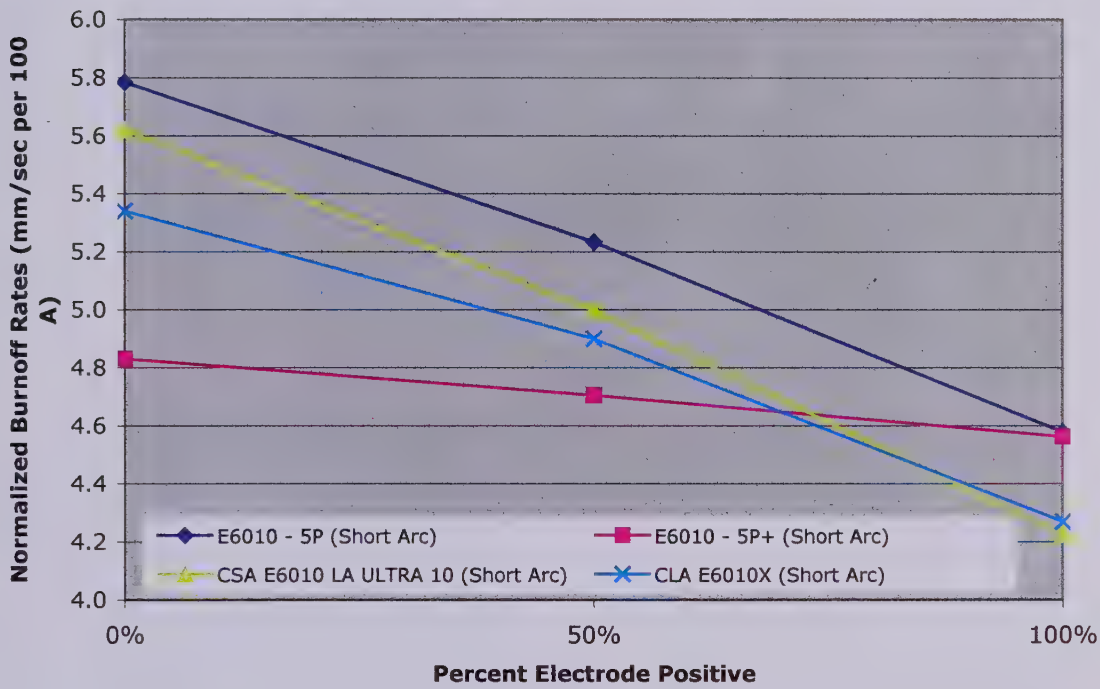
electrode lengths consumed and average welding times. Melting rates were calculated from the averages of the electrode weights consumed and average welding times. Deposition rates were calculated from the weight difference in the base metal and the average welding times. All rates were normalized to a welding current of 100 Amperes. Deposition efficiencies were calculated by comparing the melting rates to the deposition rates to arrive at a ratio of weld metal removed from the electrode to weld metal deposited on the base plate. It is important to note that the weight and the metal content of the coating were not factored in the calculations. The electrode weights before and after welding included the electrode coating.

Additional parameters tested included short and long arc conditions for the 7016 and 7018 electrodes (FRX E7016-1Ni and E7018-1+). The two conditions were produced by the manually adjusting the length of the arc during welding.

Results and Discussion

D.C. and A.C. Square Wave Welding Using EXX10

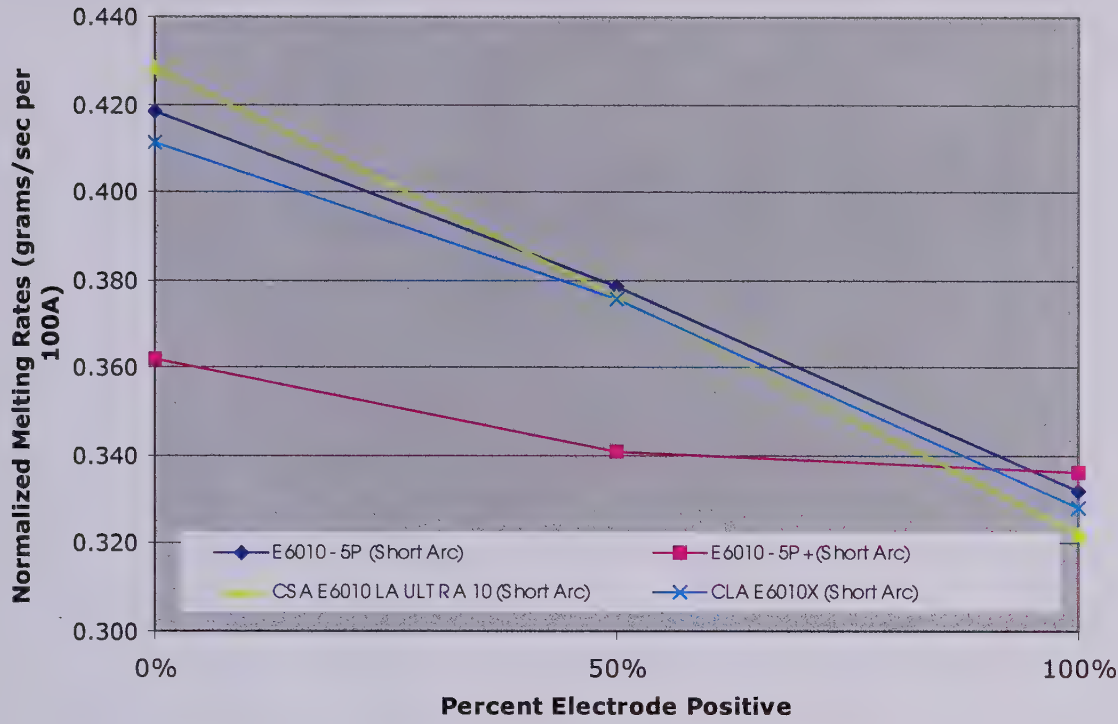
The electrodes used to investigate the operating characteristics of EXX10 electrodes included E6010-5P, E6010-5P+, CSA E6010 LA ULTRA 10, and CLA E6010X. All performance values have been normalized to 100 amperes.



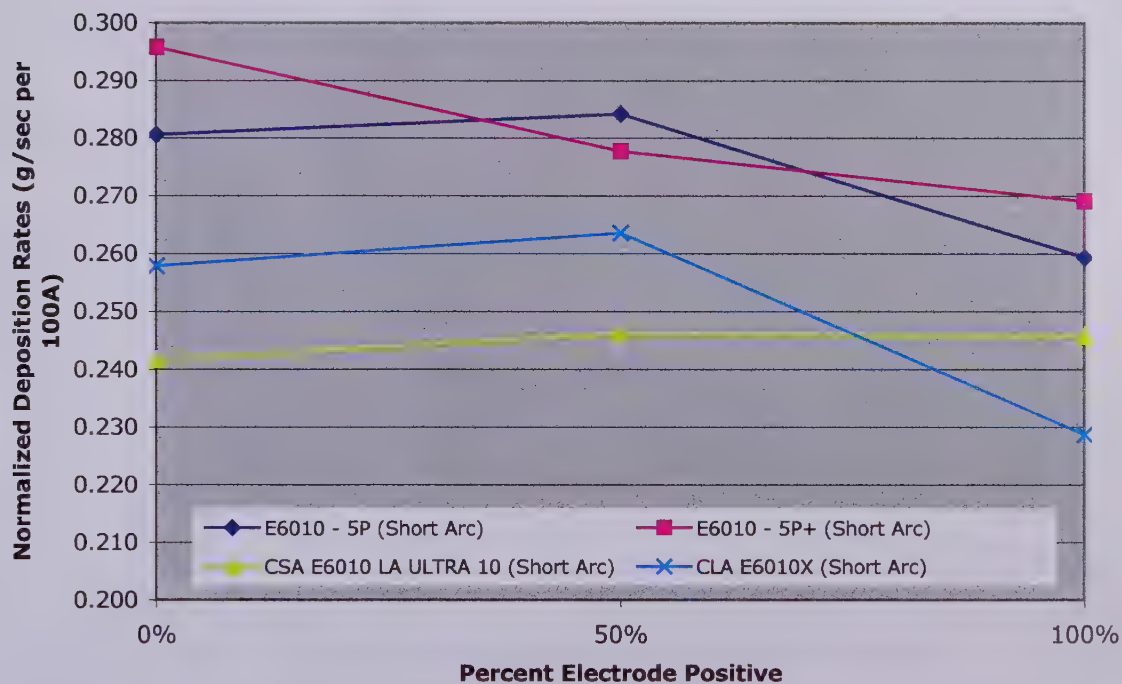
Graph 1. – Normalized Burnoff Rates

The profiles displayed are the amount of metal lost from the electrodes as they are consumed in the arc. The general profile is what would be expected from EXX10 electrodes, increasing electrode burnoff rate with decreasing electrode positive polarity. It would appear that the melting rate of the E6010-5P+ electrode is less sensitive to the polarity than the other electrodes.

The normalized deposition and deposition rates can be found in graphs 2 and



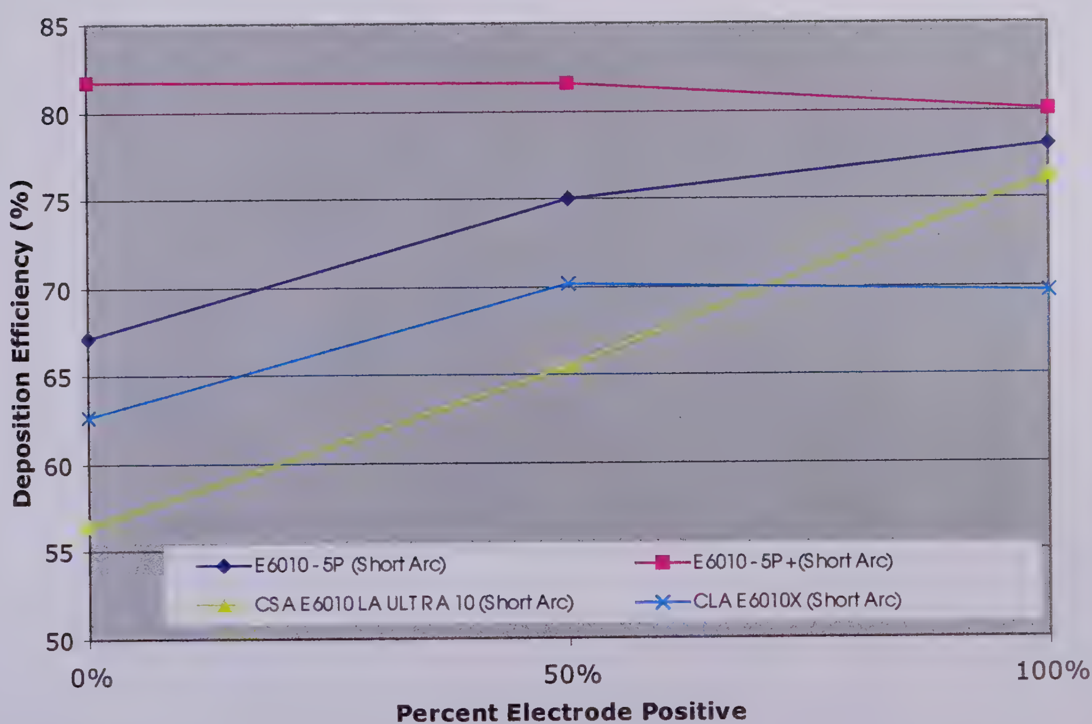
Graph 2. – Normalized Melting Rates



Graph 3. – Normalized Deposition Rates

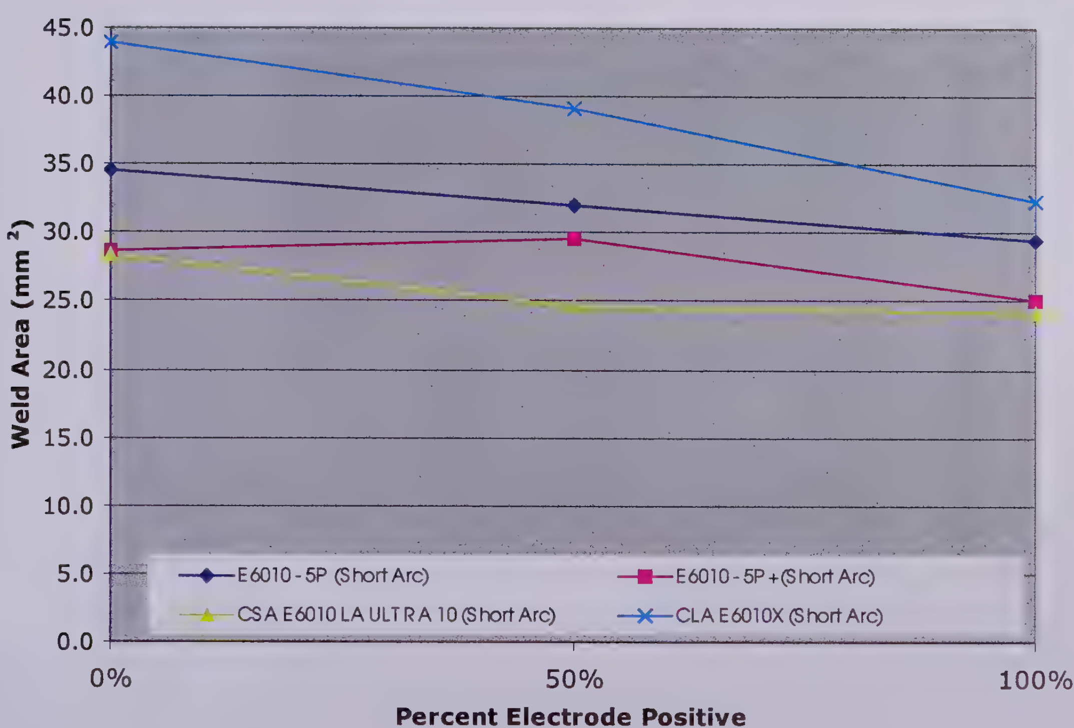
3 on page 19. The melting rates are very similar to the burnoff rates, as expected, as they are based on the mass of the metal removed from the electrode during welding rather than length.

The deposition rates are very different from the burnoff and melting rates as this rate assesses the amount of metal that was transferred to the workpiece during the welding process. The general overall shift to lower masses can be explained by burnoff of the flux, which was included in the assessment of the melting rates but not factored out in the deposition rates. Differences in between the melting rates and the deposition rates are illustrated in Graph 4, the deposition efficiency.



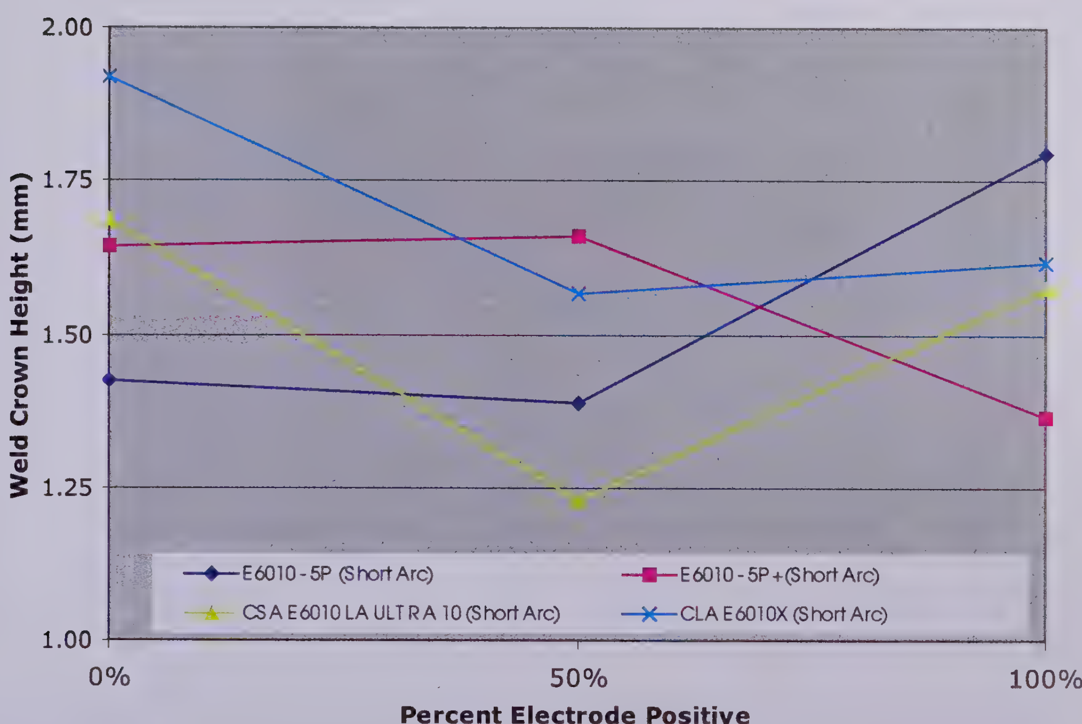
Graph 4. – Deposition Efficiency

From the deposition efficiency it is clear that E6010-5P+ appears to be the best performing and most consistent over all the polarities. The variation in the other electrodes suggests that an increasing amount of metal is transferred from the electrode to the workpiece with increasing electrode positive polarity. The difference suggests that there is increasing spatter with increasing electrode negativity. Another point of interest in the results is the relative smoothness of the deposition efficiency profiles as the polarity is switch from electrode negative through AC to electrode positive. If significant delays were experienced with arc reignition it would be expected that the deposition efficiency would be at its lowest point at 50% electrode positive (AC).

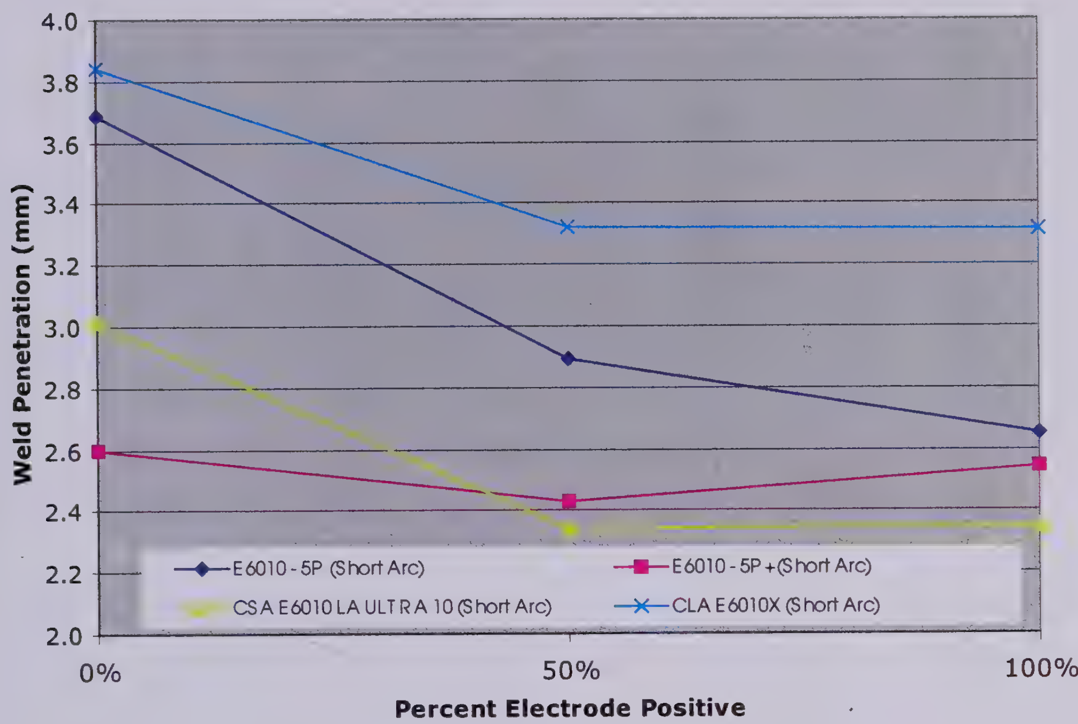


Graph 5. – Average Weld Area

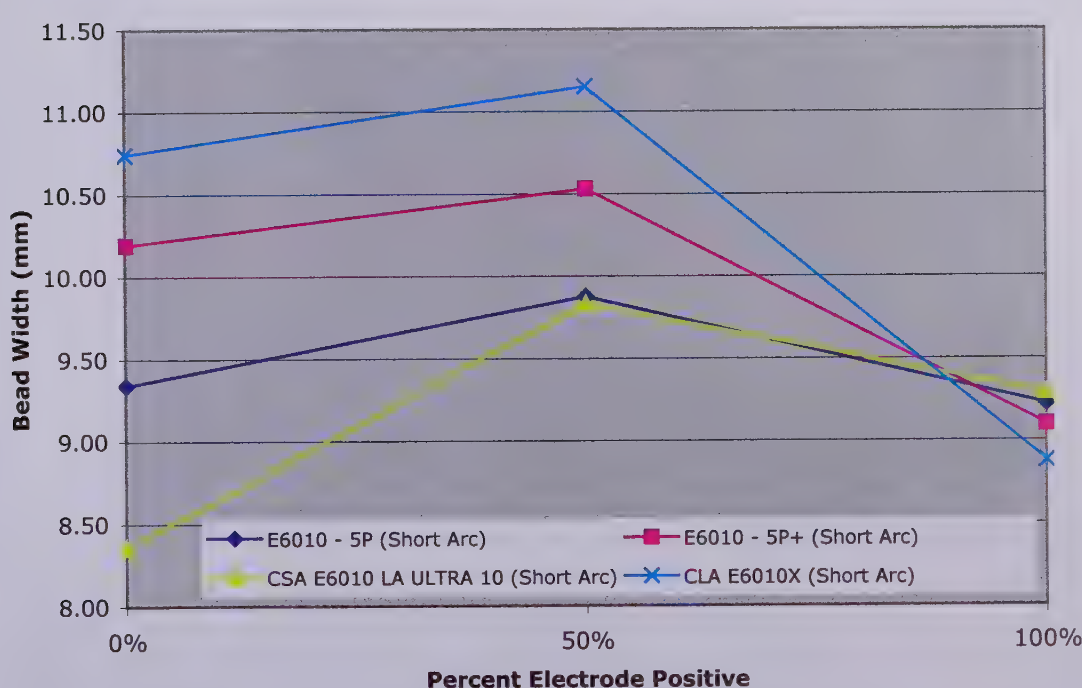
The graph of the average weld areas over the different polarities is the average value taken between at cross sections 1.5" from the start and end of the weld. It would appear that the weld area increases with decreasing electrode positive polarity. The weld area might be expected to correspond with weld reinforcement (crown height), weld penetration and weld bead width, however, when reviewing the results in graphs 6 through 8 this does not appear to always be the case. It would appear that there is some variation in the profile and shape of the welds produced under the different polarities. These graphs were also developed from average values measured from cross sections 1.5" from the start and end of the weld.



Graph 6. – Average Weld Reinforcement (Crown Height)



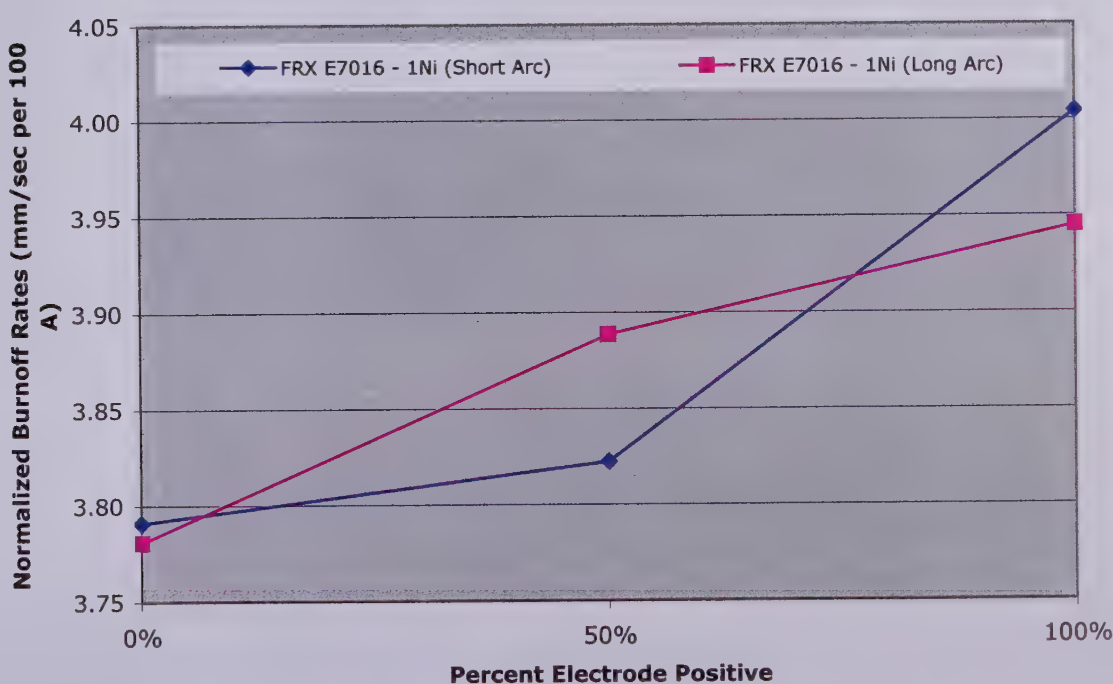
Graph 7. – Average Weld Penetration



Graph 8. – Average Weld Bead Width

The best performers for the EXX10 electrodes tested appear to be the E6010-5P+ and then the E6010-5P. These electrodes had performance profiles that proved to be the most linear over all of the polarities tested. The results further suggest that the crown width under AC polarity is highest for E6010-5P and at its lowest for the other EXX10 electrodes tested. It would also appear that the bead width is at its largest value for all EXX10 electrodes when welded using AC. This observation suggests that arc instability during polarity changes is causing changes in bead width during SMAW welding.

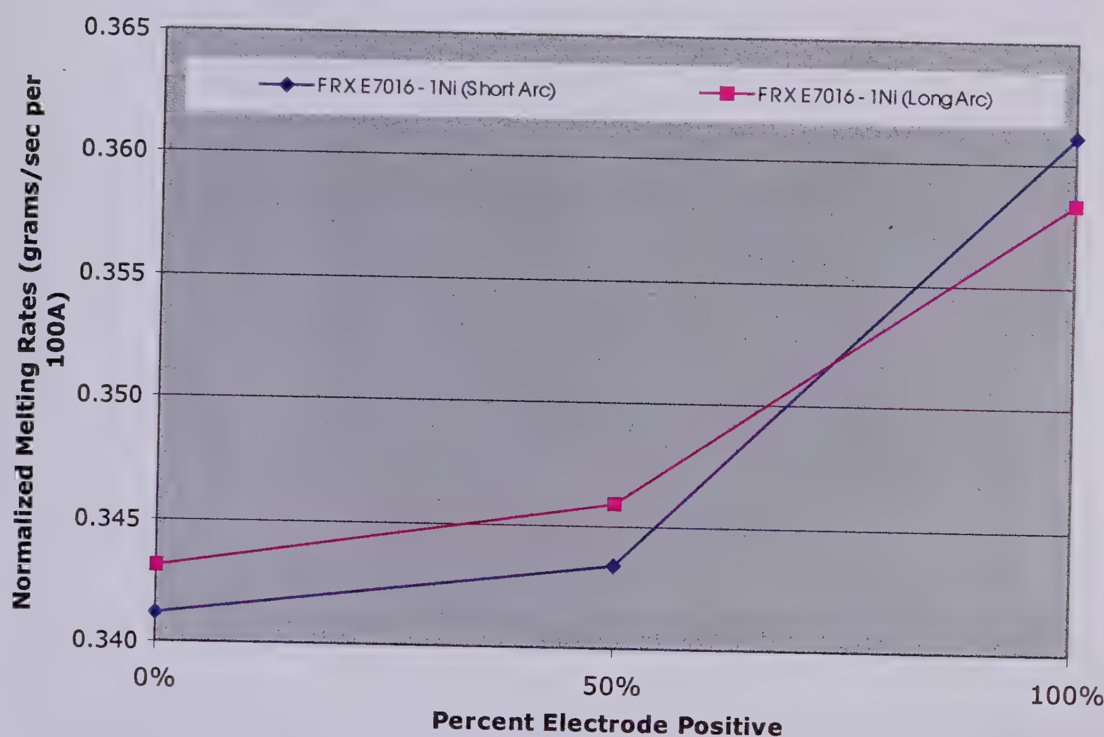
The next set of tests involved testing EXX16 and EXX18 electrodes under the same polarity conditions as the EXX10 electrodes expanded to different arc conditions, long and short.



Graph 9. – Normalized Burnoff Rates

D.C. and A.C. Square Wave Welding Using E7016 - 1Ni

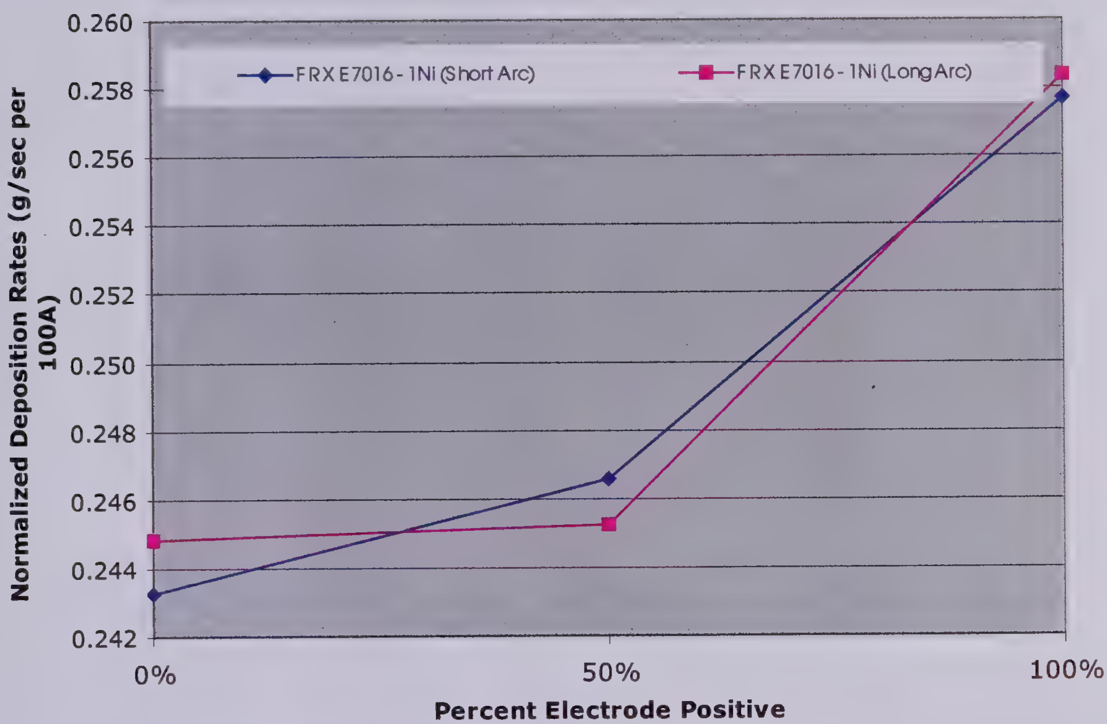
The normalized burnoff rates can be observed in graph 9 on the previous page. The profiles are slightly different, however, the difference is not very much and could be explained by accuracy limits of the tape measure used (±0.5 mm). The normalized melting rates give a more accurate assessment of electrode consumption over the different polarities.



Graph 10. – Normalized Melting Rates

The profiles for the melting rates appear to be very close, however, it would appear that the electrode is consumed faster at electrode positive polarity than at AC or electrode negative. This observation is counter to convention that predicts higher electrode melting under electrode negative conditions. It would also appear that the electrode is consumed faster under long arc

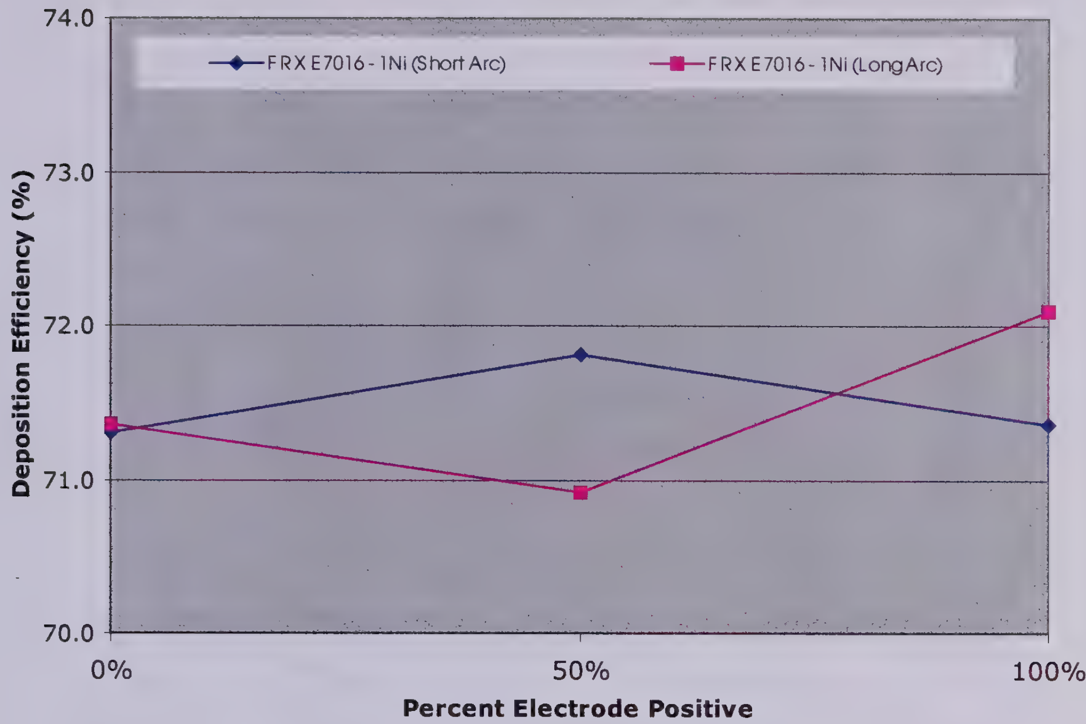
conditions at electrode negative and AC polarity. At electrode positive polarity the reverse appears to be indicated with higher consumption rates using a long arc than rates using a short arc.



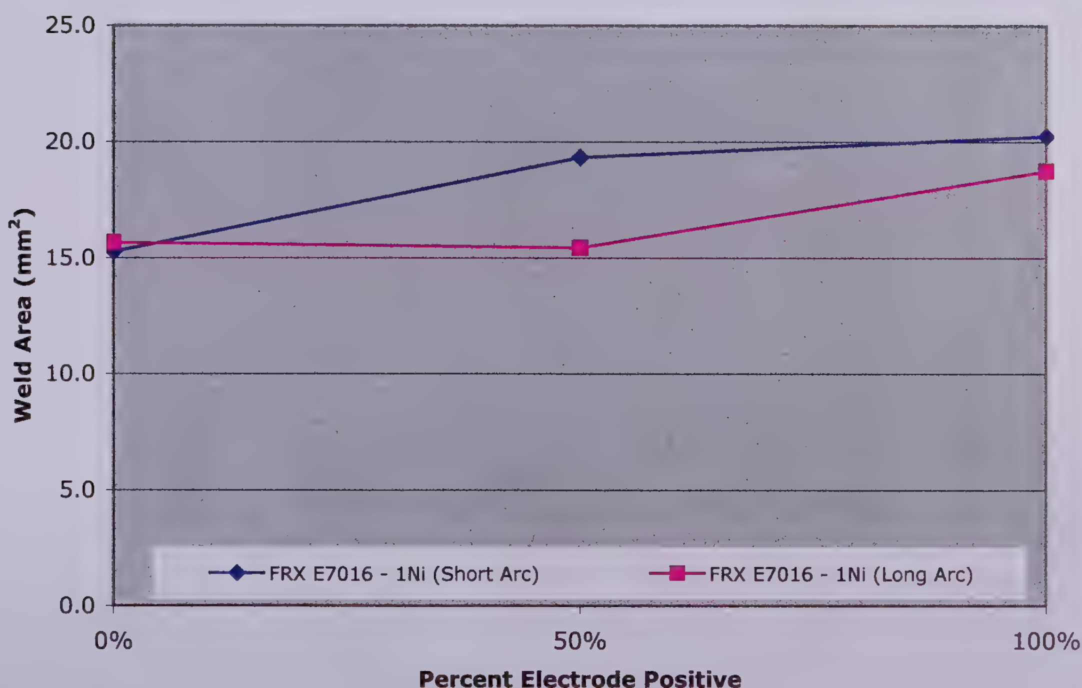
Graph 11. – Normalized Deposition Rates

Deposition rates appear to follow profiles very similar to that for the melting rates with differences indicating slightly more deposition using a long arc under electrode positive conditions and the reverse under AC conditions.

The deposition efficiency suggests that there are only slight differences between the amount of metal removed from the electrode and the amount deposited on the work piece. There appears to be slightly more variation when a longer arc is used and the values at the different polarities are within 1.5% of each other compared to 1.0% when using a short arc.

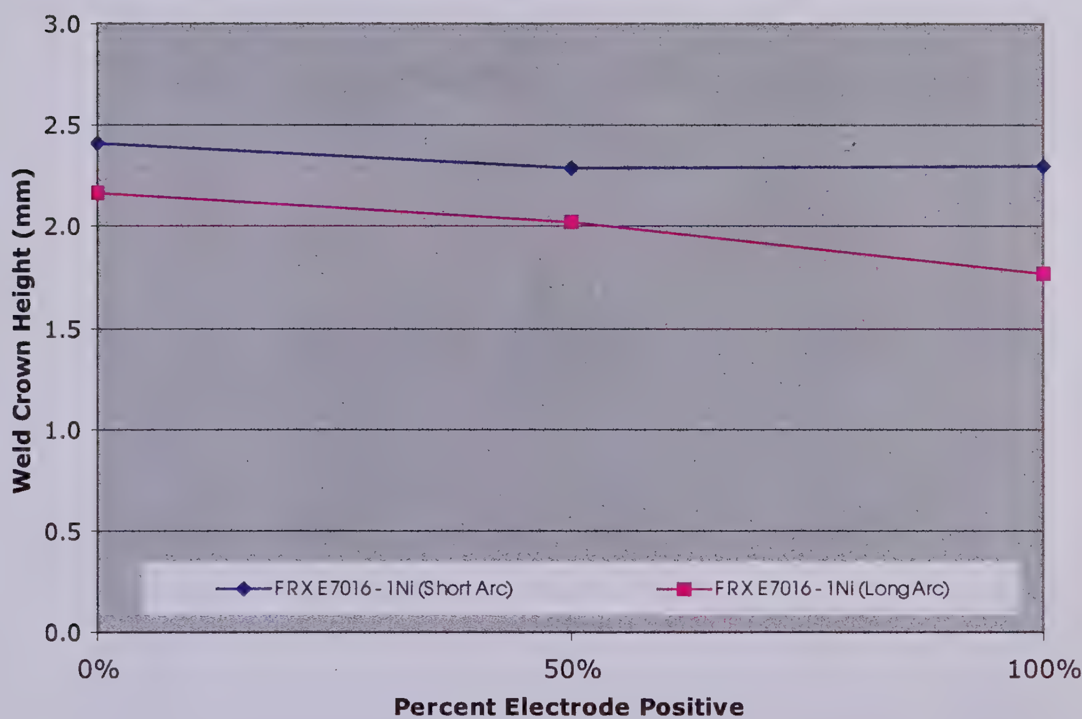


Graph 12. – Normalized Deposition Rates



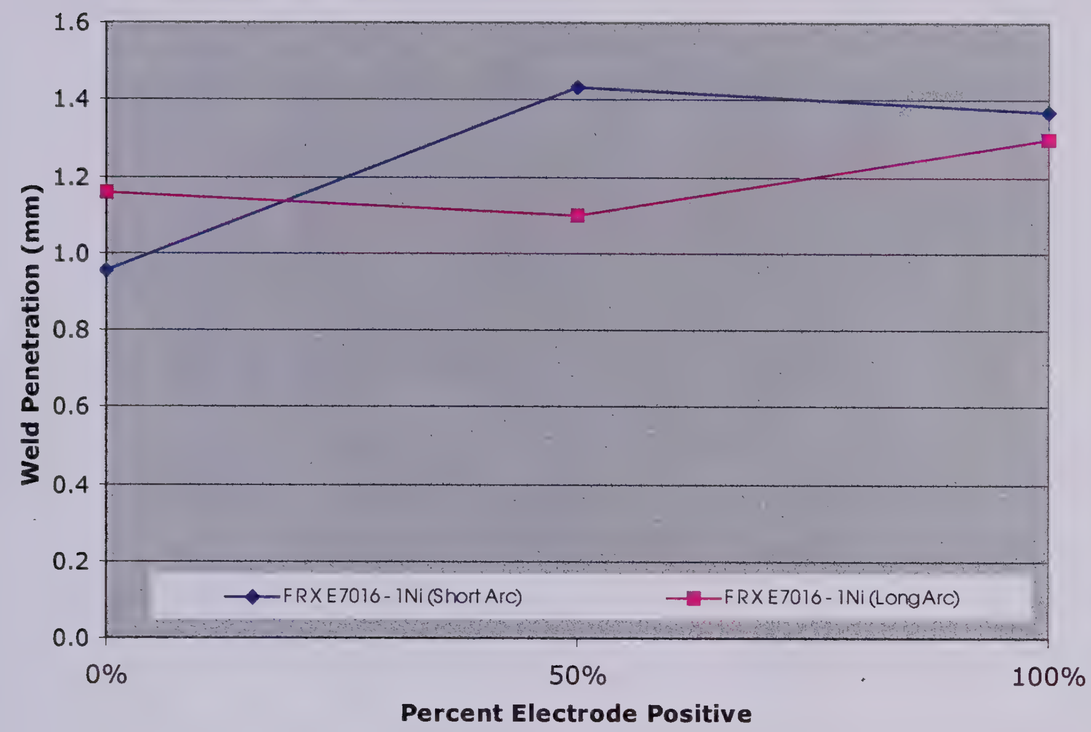
Graph 13. – Average Weld Area

Comparing the different rates calculated for E7016-1Ni against the results from the EXX10 electrodes tested it would appear that most of the trends developed are opposite to each other. This observation would suggest that making performance predictions according to convention outlined in referenced literature sources is quite limited with experimental testing being the most accurate, albeit more laborious, technique for assessing electrode performance under different electrode polarities.

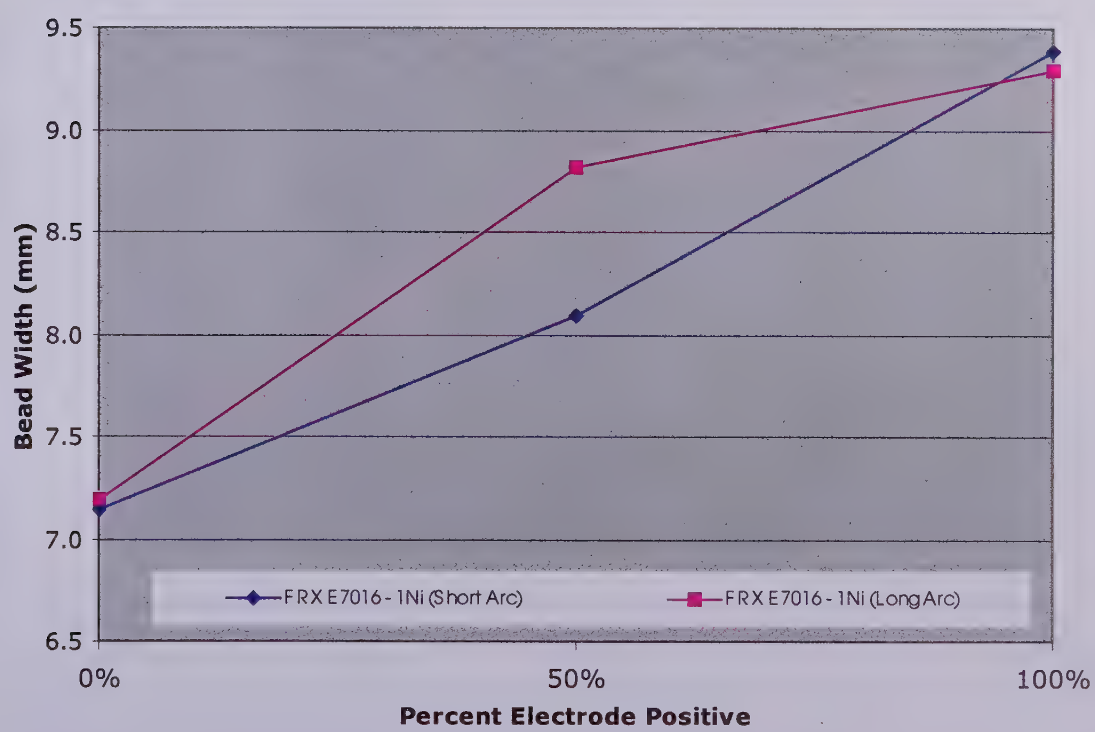


Graph 14. – Weld Reinforcement (Crown Height)

Reviewing graphs 13 through 16 it would appear that there are a few differences in the weld macrostructures between the two arc conditions. It would appear that the shorter arc produced slightly larger weld areas, higher crowns but narrower welds at most polarities. The trends also appear to



Graph 15. – Average Weld Penetration

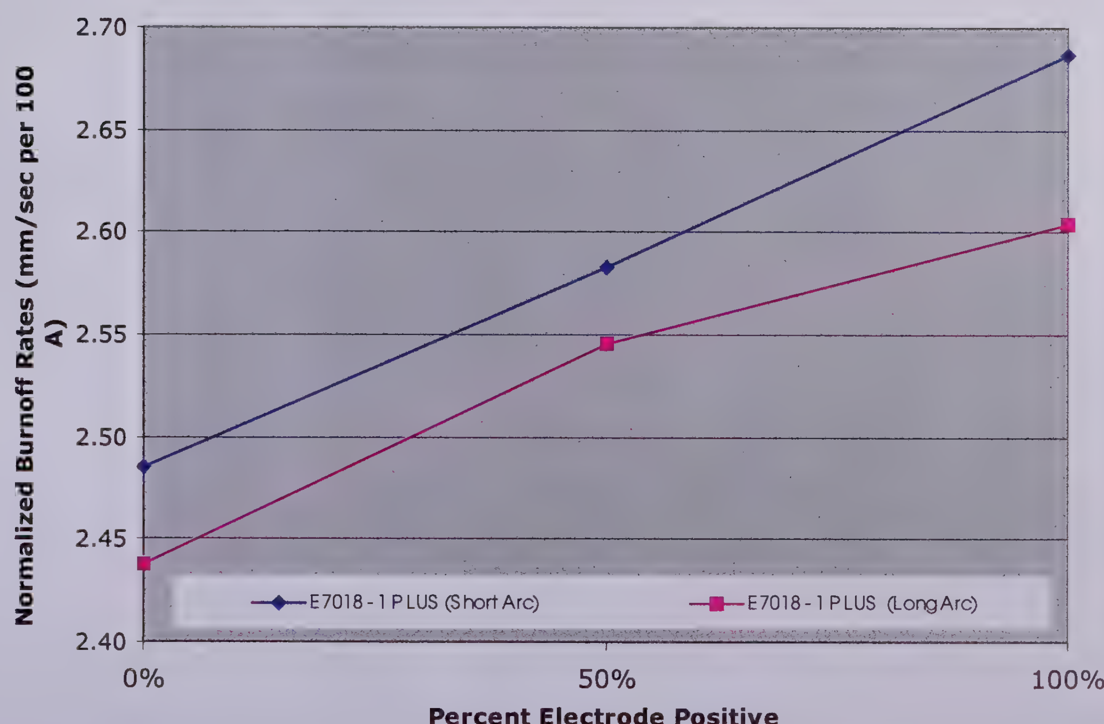


Graph 16. – Average Weld Bead Width

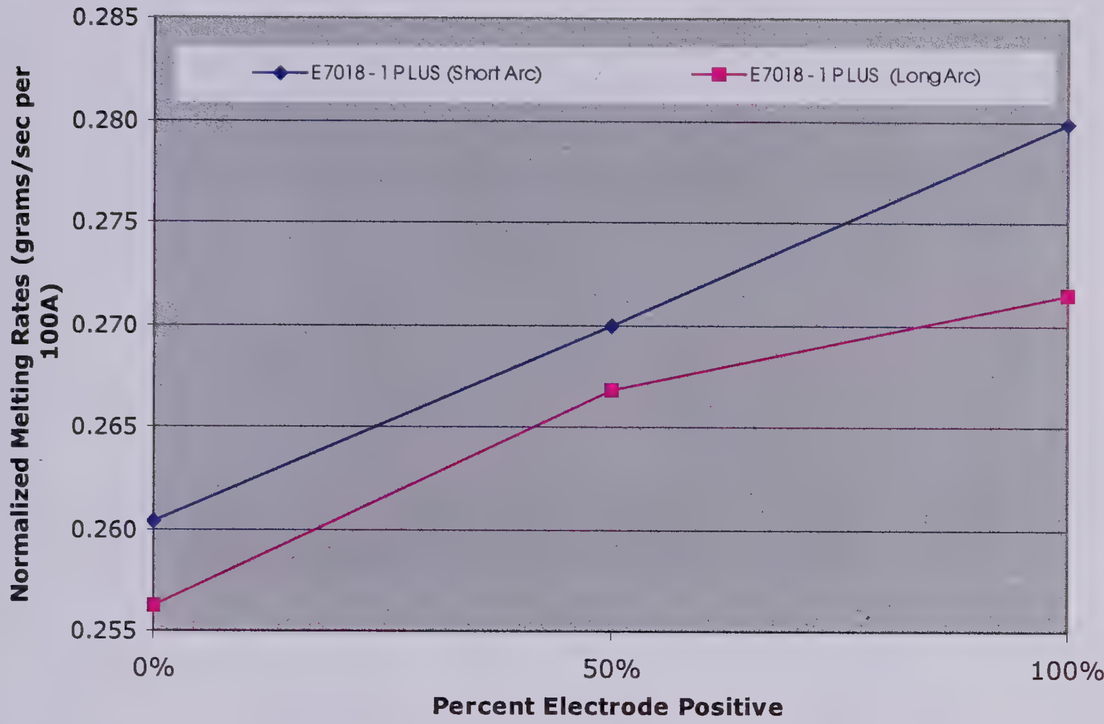
increase for weld area and bead width and decrease for weld reinforcement with increasing electrode positive polarity. Weld penetration appears to bounce around with the largest and smallest value found for short and long arc lengths, under AC polarity.

D.C. and A.C. Square Wave Welding Using E7018 – 1 PLUS

Reviewing the burnoff rates and the melting rates finds little difference between the two graphs. It would appear that, as with E7016-1Ni, electrode consumption appears to increase with increasing electrode positive polarity. It would also appear that the electrode is consumed faster with the shorter arc with the difference maximized at the 100% electrode positive polarity level.



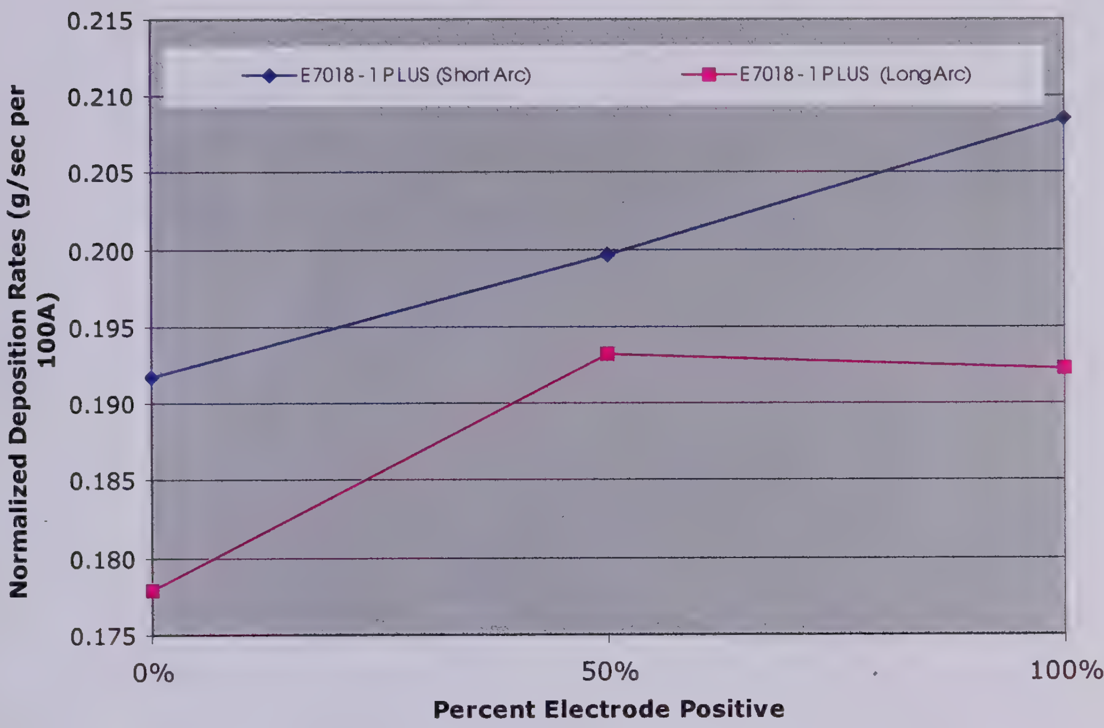
Graph 17. – Normalized Burnoff Rates



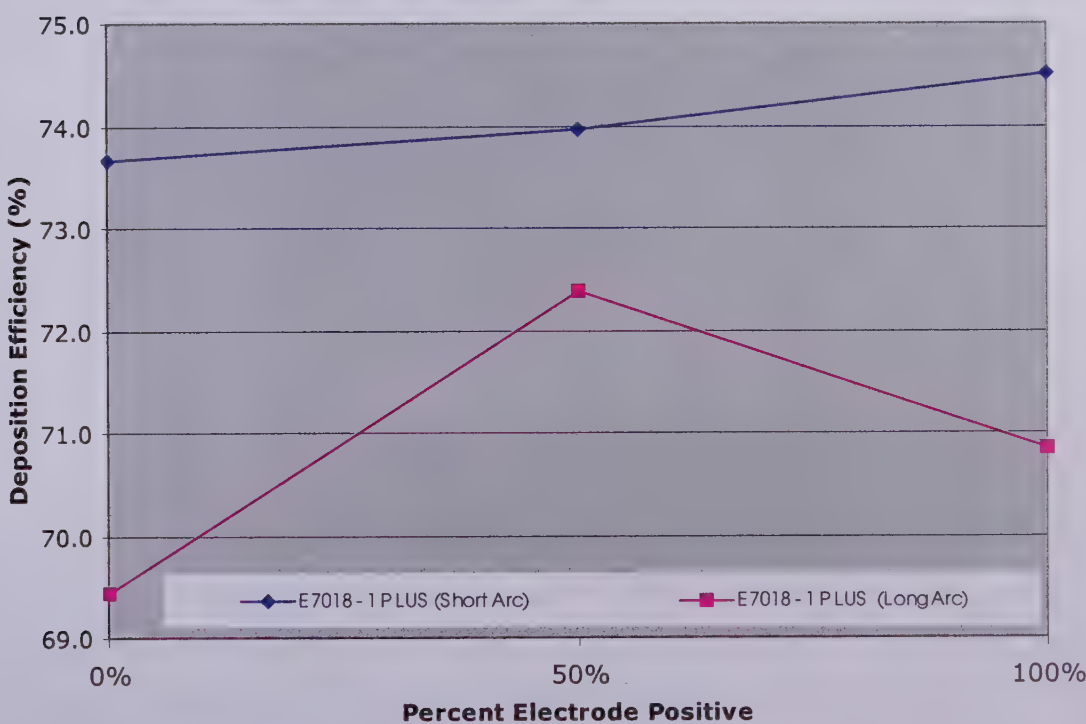
Graph 19. – Normalized Melting Rates

The burnoff and melting rate profiles have trends similar to those found for the E7016-1Ni electrodes and opposite to those developed for the EXX10 electrodes. The deposition profiles for the E7018-1+ electrodes follow the same trend as the E7016-1Ni electrodes; however, the performance profiles are much smoother. The short arc produces higher deposition rates and a smoother increasing trend with increasing electrode positive polarity. The deposition profiles have again slopes opposite to the profiles developed for the EXX10 electrodes.

The deposition efficiencies for the E7018-1+ electrodes closely resemble the profiles developed for the depositions rates. The short arc condition appears to be the most efficient and the AC polarity appears to be the most efficient when using a long arc. It would appear that AC polarity provides superior



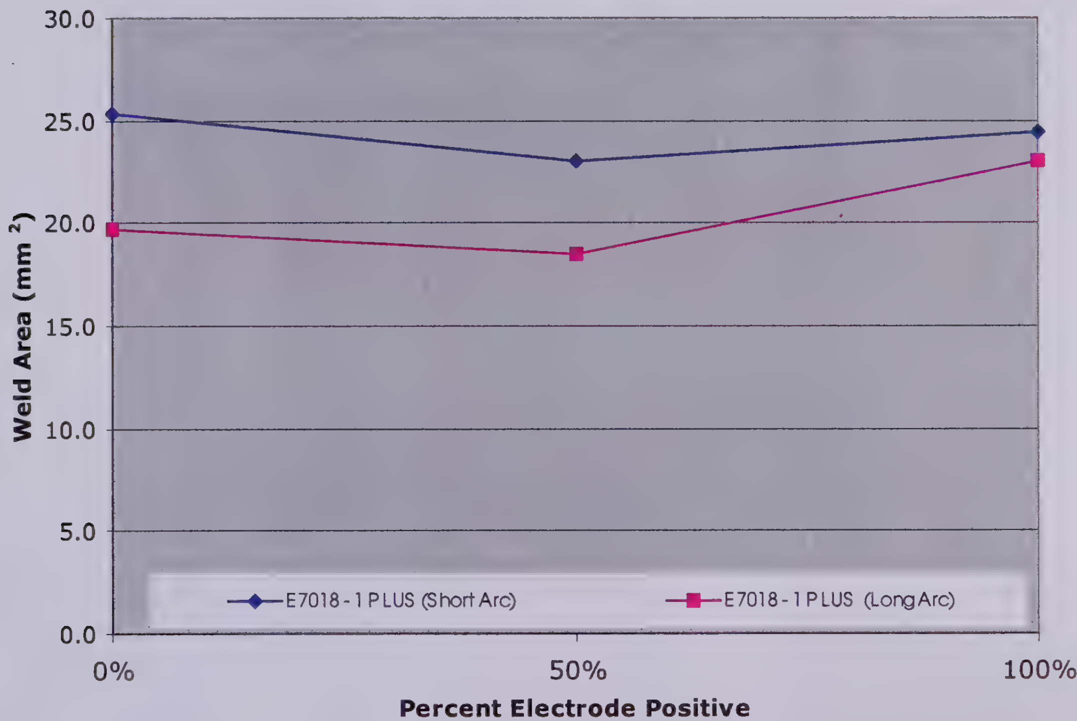
Graph 20. – Normalized Deposition Rates



Graph 21. – Deposition Efficiency

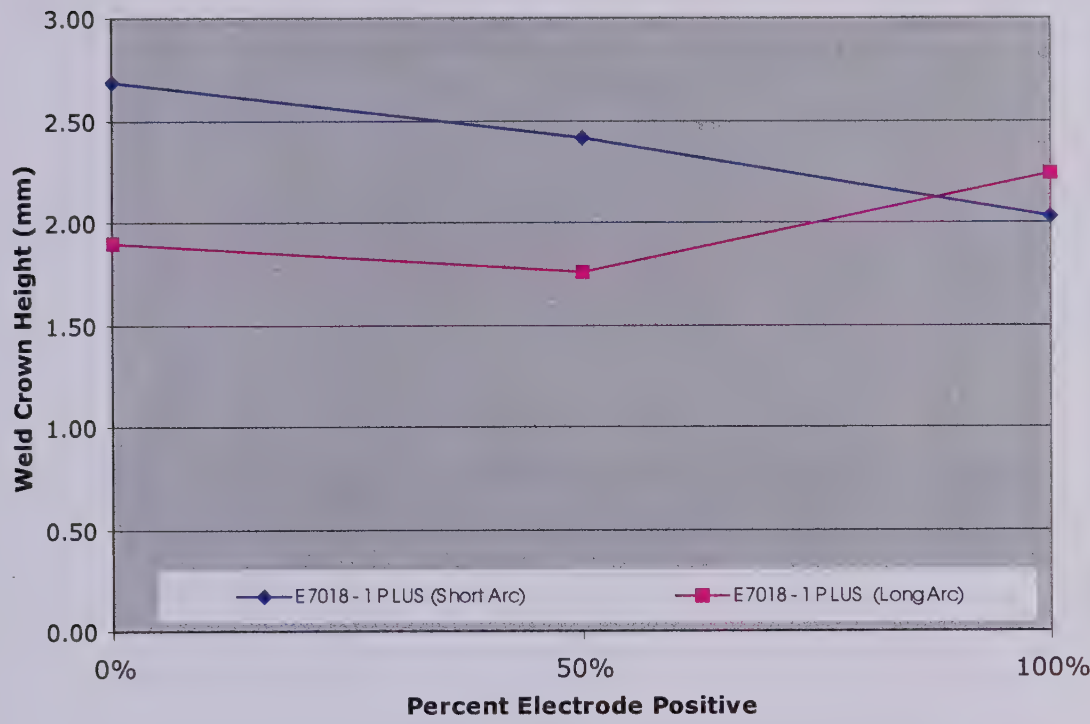
deposition performance and efficiency when used with a long arc.

After reviewing graphs 22 through 25 it is clear that a few trends can be observed in the macrostructure developed for the E7018-1+ electrode at the various polarities. Graph 22 would suggest that larger weld areas are produced at short arc conditions with the lowest values reported under AC

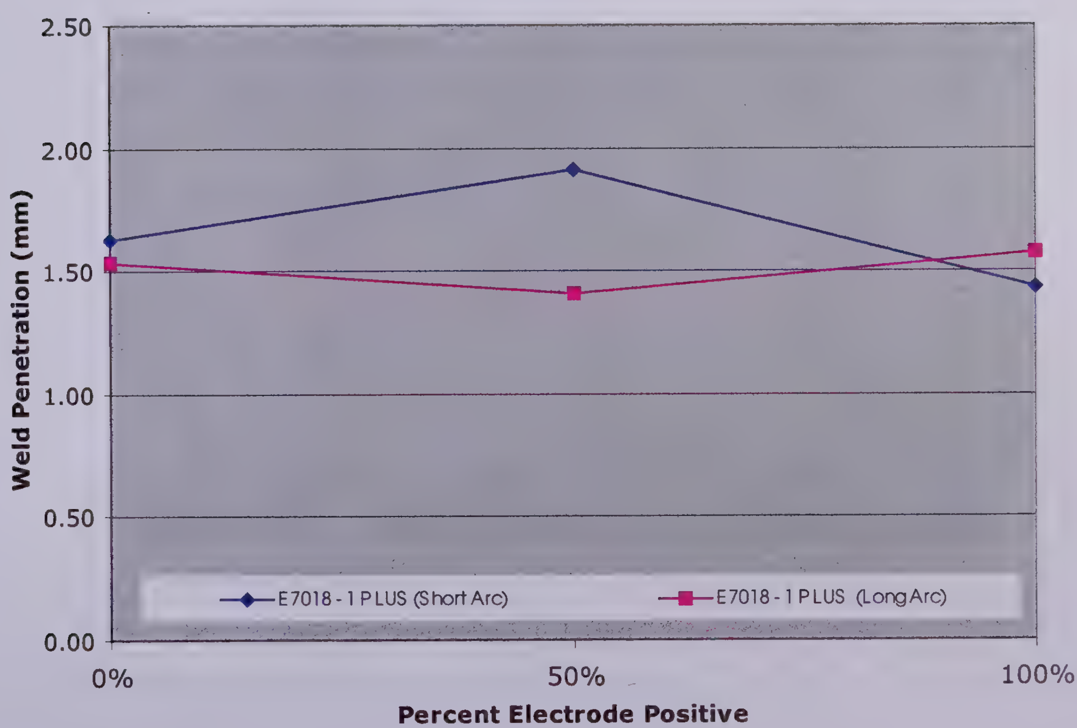


Graph 22. – Average Weld Area

conditions. Graph 23 suggests that weld reinforcement tends to increase with increasing electrode positive polarity with a short arc and tends to decrease with a long arc. AC polarity combined with a long arc appears to produce the least amount of weld reinforcement. Graph 24 illustrates weld penetration profiles that have little variation between different polarities.

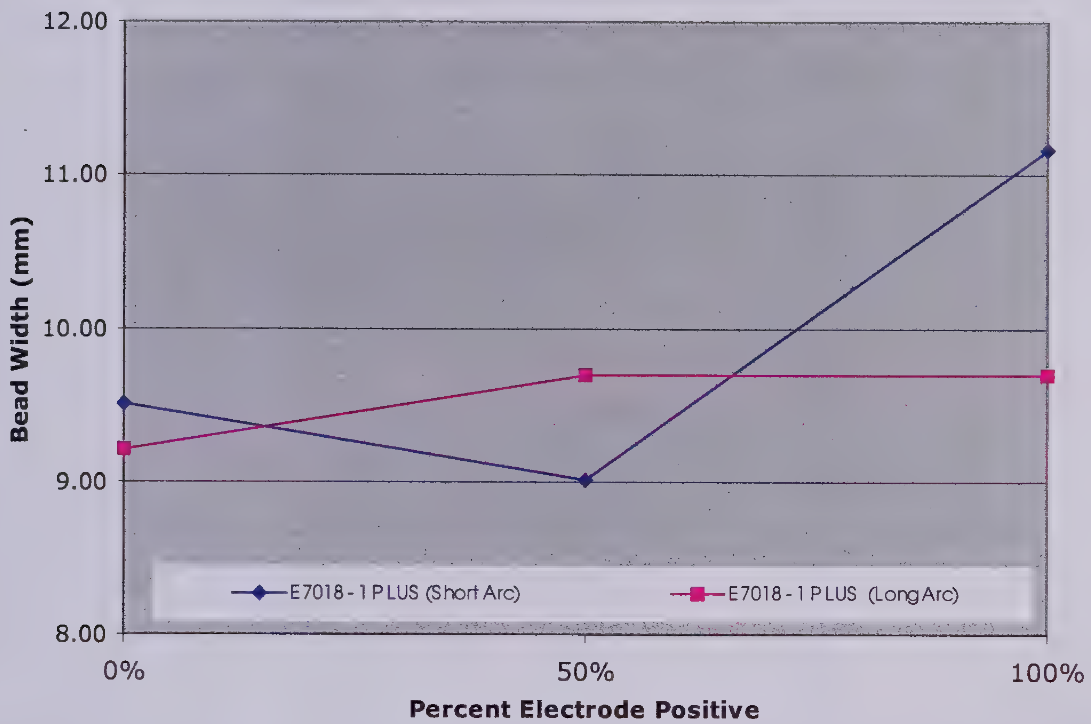


Graph 23. – Weld Reinforcement (Crown Height)



Graph 24. – Average Weld Penetration

The short arc condition delivers slightly deeper penetration under electrode negative and AC polarities, however, at electrode positive deeper penetration is achieved with a longer arc.



Graph 25. – Average Weld Bead Width

The final graph of the average weld bead width indicates a slight variation with polarity. AC polarity appears to produce the widest bead widths using a long arc and narrowest using a short arc. At the other polarities it would appear that wider beads are produced using shorter arcs with the greatest difference observed at electrode negative polarity.

Comparing the weld dimensions developed using the E7018-1+ electrodes with those developed using E7016-1Ni several observations can be made. The trends for the weld area developed using both short arc and long arc appear to be in opposite directions with weld area increasing with increasing electrode positive polarity for E7016-1Ni and decreasing for E7018-1+. Trends for weld reinforcement appear to be similar for short arc lengths, decreasing with increased electrode positive polarity, but appear to be reversed at long arc lengths. Weld penetration appears to be jump around between polarities for both electrodes; however, it is interesting to note that penetration appears to be highest and lowest for both electrodes using AC using short and long arcs, respectively. The largest performance deviation between the two electrodes appears to be with the bead widths produced. Bead widths for the E7016-1Ni electrodes appear to share a similar profile under both long and short arc conditions, steadily increasing with increasingly positive polarity. Bead widths for the E7018-1Ni electrodes, appear to increase steadily with increasing electrode positive polarity for the long arc condition, however, under short arc conditions the data suggests that the bead width decreases slightly under AC conditions.

The raw experimental results can be found in the appendix. Appendix I contains tabulated performance and macrostructure data, Appendix II contains the raw performance and macrostructure data, and Appendix III contains pictures of all the macros developed for the investigation. All of the graphs were developed from data contained in Appendix I.

Conclusions

After reviewing all of the data for the EXX10 electrodes it would appear that the most versatile and best performing electrode, over the polarity range tested, was the E6010-5P+. The E6010-5P+ electrode had the highest and most consistent deposition efficiency and the most consistent weld penetration. The E6010-5P was a close second with considerably less deposition efficiency and increasing weld penetration with increasing electrode negativity. When comparing weld bead widths developed at the different polarities, the E6010-5P electrode had a profile that was considerably flatter and more linear than the profile developed with the E6010-5P+ electrode.

The EXX10 electrodes are usually designed for use with DC electrode positive polarity. When confronted with a problem such as arc blow the user would be most interested in alternatives that provide results similar to that expected by the original design. Using this as a benchmark to evaluate the AC performance of the various electrodes testing in this investigation, it appears that the suitability of the electrodes for use with AC depends on the requirements of the application. A list of the best and second best performers per criteria assessed would be as follows:

Deposition Efficiency:	First:	E6010-5P+
	Second:	E6010-5P
Weld Reinforcement (Crown Height):	First:	CLA 6010X
	Second:	E6010-5P+
Weld Penetration:	First:	CSA E6010 LA ULTRA 10
	Second:	CLA 6010X
Average Bead Width:	First:	CSA E6010 LA ULTRA 10
	Second:	E6010-5P

Unfortunately no one electrode proved superior over all properties so the user would have to decide which combination would work in order to effectively select an EXX10 electrode for AC use.

Further review of the results of the investigation indicate that most electrodes developed decreased crown height and increased weld bead width when used with AC. This suggests that the arc is still relatively unstable with the EXX10 electrodes, even with the square wave AC, and the operator will have difficulty developing a weld bead comparable to that developed with the designed polarity.

Comparing the performances of the E7016 and E7018 electrodes the effects of the higher iron content of the flux are illustrated at high and low arc lengths. The higher iron content appears to effect differences between low and high arc lengths for deposition efficiencies, crown heights and bead widths. The higher iron content of the flux makes the deposition of the E7018 electrode much more efficient using a short arc than a long arc. Disposition efficiencies for the E7016 electrodes do not display the same clear difference. Using a short arc increases electrode melting via electrode shorting which in turn increasing the amount of metal transfer to the work piece without spattering as experienced with longer arc lengths. The same mechanism explains the higher crown heights and narrower weld beads developed using a short arc with the E7018 electrodes. Similar trends were found using the E7016 electrodes, however, they were not quite as pronounced. Predictably, the weld beads developed using the E7018 electrodes, with the higher flux iron content, are considerably larger than those developed with E7016 electrodes.

Using the criteria previously used to assess AC performance in EXX10 electrodes to assess E7016 and E7018 electrodes it is clear to see the difference in performance between the two electrodes. There is considerably more variation between deposition efficiencies, crown heights, weld penetrations and bead widths at 50% and 100% electrode positive for the E7018 electrode than the E7016 electrode. This indicates that it would be much easier for an operator using an E7016 electrode to switch to AC than it would be when using an E7018 electrode.

	Original Design	Deposition Efficiency	Crown Height	Weld Penetration	Bead Width
E6010 - 5P (Short Arc)	DC +	DC +	DC +	DC -	AC
E6010 - 5P+ (Short Arc)	DC +	DC -	AC	DC -	AC
CSA E6010 LA ULTRA 10 (Short Arc)	DC +	DC +	DC -	DC -	AC
CLA E6010X (Short Arc)	DC +	DC +	DC +	DC -	AC
FRX E7016 - 1Ni (Short Arc)	AC/DC +	AC	DC -	AC	DC +
FRX E7016 - 1Ni (Long Arc)	AC/DC +	DC +	DC -	DC +	DC +
E7018 - 1 PLUS (Short Arc)	AC/DC +	DC +	DC -	AC	AC
E7018 - 1 PLUS (Long Arc)	AC/DC +	AC	DC +	DC +	DC +

Figure 7. – Polarities for Maximum Values

After reviewing all the information from this investigation it can be concluded that there is no one electrode that provides superior performance across all polarities. It would appear that electrode selection is highly dependant on the requirements of the application. Electrodes not intended or designed for AC applications (EXX10 and E7018) can be used, however, careful

consideration must be made to properties that are critical to the application and trade offs that will have to be made before the appropriate electrode can be selected. Figure 7 summarizes the polarities at which maximum values for different properties were determined during this investigation of the various electrodes.

Although considerable insight was derived from the information collected during this investigation, the conclusions were drawn from a rather limited sample size. There is considerable scatter in the results and it is difficult to draw solid conclusions from electrodes tested at only three different polarity settings. Originally the experiment was intended to test electrode performance at polarities that would be incrementally increased from 100% electrode negative to 100% electrode positive. Performing such tests would provide considerably more information on the electrode performance as well as the ideal electric configuration that would provide the maximum performance. Unfortunately, the power source selected for the experiment, the Dynasty 300, was unable to provide the range of polarities for SMAW and the Miller Syncrowave 300 power source has to be used instead. As a result of the substitution only three polarities could be tested, DC positive, AC, and DC negative (0%, 50% and 100% electrode positive, respectively). If this investigation was to be continued it would be recommended that the polarity range be expanded to include smaller increments and more tests were performed at each polarity. Decreasing the increment size would improve the resolution to help determine the optimum polarity and increasing the number of samples would improve the statistical confidence of the results reducing the effects of scatter.

To further expand the investigation, it would also be recommended that the experiment be expanded to include a wider range of electrodes and suppliers. Including more electrodes in the investigation would add to the value and usefulness of the data when trying to determine the best electrode for the required performance and electrical configuration.

References

[1] American Welding Society, *Welding Processes*, Welding Handbook, Sixth Edition, Section Two, p. 45.

[2] T.S. Thomson, *SMAW Electrode Performance in Fusion Welding*, 1984.

[3] American Welding Society, *Welding Processes*, Welding Handbook, Fifth Edition, Section Two, p. 22.13 – 22.14.

[4] A.C. Bicknell, B.M. Patchett, *The Use of Square Wave Power with the SMAW Process to Minimize Magnetic Arc Blow*, Welding Engineering Report No.4.

[5] T.S. Thomson, *SMAW Electrode Performance in Fusion Welding*, 1984.

[6] International Institute of Welding, The Physics of Welding, 1984.

[7] International Institute of Welding, The Physics of Welding, 1984.

[8] American Welding Society, Welding Processes, Welding Handbook, Sixth Edition, Section Two, p. 66.

[9] A.C. Bicknell, B.M. Patchett, *The Use of Square Wave Power with the SMAW Process to Minimize Magnetic Arc Blow*, Welding Engineering Report No.4.

[10] Petro Shajenko, *Effects of Magnetic Field on Transfer Characteristics of Particles in an Electric Arc*, Welding Research Supplement, Welding Journal, v. 39 (2), p. 83s.

[11] American Welding Society, *Welding Processes*, Welding Handbook, Eighth Edition, Section Two, p. 68.

[12] A.C. Bicknell, B.M. Patchett, *The Use of Square Wave Power with the SMAW Process to Minimize Magnetic Arc Blow*, Welding Engineering Report No.4.

APPENDIX I

Tabulated Results

SMAW Electrode Test Results

Performance Results

September 8, 2001

Electrode Class	Percent Electrode Positive	Current (Amps)	Voltage (Volts)	Average Length Consumed (inches)	Average Length Consumed (mm)	Average Welding Time (seconds)	Average Burnoff Rate (in./sec)	Average Burning Rate (mm/sec)	Normalized Burnoff Rate (in./s per 100A)	Normalized Burnoff Rate (mm/s per 100A)	Absolute Melting Rate (grams/sec)	Normalized Melting Rate (g/s per 100A)	Deposition Rate (grams/sec)	Normalized Deposition Rate (g/s per 100A)	Deposition Efficiency (%)
E6010 - 5P (Short Arc)	100%	115	24	12.479	317.0	60.2	0.207	5.26	0.180	4.58	0.382	0.332	0.298	0.259	78.1
	50%	115	30	12.583	319.6	53.1	0.237	6.02	0.206	5.23	0.435	0.379	0.327	0.284	75.1
	0%	115	32	12.521	318.0	47.8	0.262	6.65	0.228	5.78	0.481	0.418	0.323	0.281	67.1
E6010 - 5P+ (Short Arc)	100%	115	24	12.521	318.0	60.6	0.207	5.25	0.180	4.56	0.386	0.336	0.310	0.269	80.1
	50%	115	28	11.688	296.9	54.9	0.213	5.41	0.185	4.70	0.392	0.341	0.319	0.278	81.6
	0%	115	26	12.083	306.9	55.3	0.219	5.55	0.190	4.83	0.416	0.362	0.340	0.296	81.7
CSA E6010 LA ULTRA 10 (Short Arc)	100%	115	24	11.938	303.2	62.4	0.191	4.86	0.166	4.23	0.370	0.322	0.283	0.246	76.3
	50%	115	30	10.521	267.2	46.5	0.226	5.75	0.197	5.00	0.432	0.376	0.283	0.246	65.5
	0%	115	30	12.021	305.3	47.3	0.254	6.46	0.221	5.62	0.492	0.428	0.278	0.242	56.4
CLA E6010X (Short Arc)	100%	115	30	11.854	301.1	61.3	0.193	4.91	0.168	4.27	0.377	0.328	0.263	0.229	69.7
	50%	115	40	11.896	302.2	53.6	0.222	5.63	0.193	4.90	0.432	0.376	0.303	0.264	70.2
	0%	115	38	11.979	304.3	49.6	0.242	6.14	0.210	5.34	0.473	0.411	0.297	0.258	62.7
FRX E7016 - 1Ni (Short Arc)	100%	115	22	15.500	393.7	85.5	0.181	4.61	0.158	4.00	0.415	0.361	0.296	0.258	71.4
	50%	115	22	15.604	396.3	90.2	0.173	4.40	0.150	3.82	0.395	0.343	0.284	0.247	71.8
	0%	115	20	15.646	397.4	91.2	0.172	4.36	0.149	3.79	0.392	0.341	0.280	0.243	71.3
FRX E7016 - 1Ni (Long Arc)	100%	115	28	15.271	387.9	85.5	0.179	4.54	0.155	3.95	0.412	0.358	0.297	0.258	72.1
	50%	115	30	15.875	403.2	90.2	0.176	4.47	0.153	3.89	0.398	0.346	0.282	0.245	70.9
	0%	115	22	15.604	396.3	91.2	0.171	4.35	0.149	3.78	0.395	0.343	0.282	0.245	71.4
E7018 - 1 PLUS (Short Arc)	100%	135	20	12.208	310.1	85.5	0.143	3.63	0.106	2.69	0.378	0.280	0.282	0.209	74.5
	50%	132	24	12.104	307.4	90.2	0.134	3.41	0.102	2.58	0.356	0.270	0.264	0.200	74.0
	0%	135	20	12.042	305.9	91.2	0.132	3.36	0.098	2.49	0.351	0.260	0.259	0.192	73.7
E7018 - 1 PLUS (Long Arc)	100%	135	22	11.833	300.6	85.5	0.138	3.52	0.103	2.60	0.367	0.271	0.260	0.192	70.9
	50%	133	22	12.021	305.3	90.2	0.133	3.39	0.100	2.55	0.355	0.267	0.257	0.193	72.4
	0%	135	22	11.813	300.0	91.2	0.130	3.29	0.096	2.44	0.346	0.256	0.240	0.178	69.5

SMAW Electrode Test Results

lacrostructure Features

September 8, 2001

Electrode Class	Percent Electrode Positive	Section Position - 1.5" After Weld Start						Section Position - 1.5" Before Weld End						Average Values					
		Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
E6010 - 5P (Short Arc)	100%	30.28	1.8	2.7	4.1	9.3	12.0	28.55	1.8	2.6	4.0	9.2	11.3	29.42	1.8	2.7	4.1	9.2	11.7
	50%	31.57	1.4	2.7	4.7	9.9	13.0	32.31	1.4	3.1	4.7	9.8	12.5	31.94	1.4	2.9	4.7	9.9	12.7
	0%	35.42	1.5	3.6	5.3	9.7	12.8	33.87	1.3	3.7	5.2	9.0	12.6	34.64	1.4	3.7	5.3	9.3	12.7
E6010 - 5P+ (Short Arc)	100%	24.23	1.3	2.4	3.9	8.9	11.6	26.00	1.4	2.7	4.0	9.3	11.8	25.11	1.4	2.5	3.9	9.1	11.7
	50%	31.41	1.8	2.5	4.4	10.8	12.1	27.65	1.5	2.3	4.2	10.3	12.8	29.53	1.7	2.4	4.3	10.5	12.5
	0%	29.94	1.7	2.7	5.0	10.4	13.2	27.30	1.5	2.5	4.2	10.0	12.4	28.62	1.6	2.6	4.6	10.2	12.8
CSA E6010 LA ULTRA 10 (Short Arc)	100%	23.37	1.6	2.4	3.6	9.0	11.2	24.91	1.6	2.3	4.2	9.6	12.1	24.14	1.6	2.3	3.9	9.3	11.6
	50%	23.92	0.9	2.5	4.9	10.7	13.5	25.32	1.6	2.2	4.4	9.0	12.3	24.62	1.2	2.3	4.7	9.8	12.9
	0%	30.93	1.5	3.5	5.5	8.2	13.0	25.86	1.9	2.5	4.3	8.5	11.0	28.40	1.7	3.0	4.9	8.4	12.0
CLA E6010X (Short Arc)	100%	31.34	1.6	3.4	5.5	8.7	13.0	33.25	1.7	3.3	5.2	9.1	11.8	32.29	1.6	3.3	5.3	8.9	12.4
	50%	37.89	1.7	3.2	5.1	10.6	13.7	40.41	1.4	3.4	5.1	11.7	14.6	39.15	1.6	3.3	5.1	11.2	14.2
	0%	44.65	2.1	3.8	6.6	10.9	14.3	43.24	1.8	3.9	6.2	10.6	14.2	43.94	1.9	3.8	6.4	10.7	14.3
FRX E7016 - 1Ni (Short Arc)	100%	21.10	2.2	1.7	2.7	9.2	10.5	19.40	2.4	1.1	2.4	9.6	10.7	20.25	2.3	1.4	2.6	9.4	10.6
	50%	18.80	2.1	1.3	2.6	8.8	10.0	19.87	2.5	1.5	2.7	7.4	9.4	19.34	2.3	1.4	2.7	8.1	9.7
	0%	15.01	2.2	1.1	2.9	7.0	8.8	15.53	2.6	0.8	2.8	7.3	9.3	15.27	2.4	1.0	2.9	7.1	9.0
FRX E7016 - 1Ni (Long Arc)	100%	18.95	1.9	1.4	3.5	9.0	11.5	18.57	1.7	1.2	3.8	9.6	11.8	18.76	1.8	1.3	3.7	9.3	11.7
	50%	16.76	2.3	1.0	3.1	9.1	10.8	14.12	1.8	1.2	3.1	8.5	10.8	15.44	2.0	1.1	3.1	8.8	10.8
	0%	14.49	2.2	1.1	3.1	7.2	9.7	16.84	2.1	1.3	2.8	7.2	9.2	15.67	2.2	1.2	3.0	7.2	9.5
E7018 - 1 PLUS (Short Arc)	100%	24.43	2.0	1.5	3.9	11.4	13.5	24.55	2.1	1.3	3.3	11.0	12.9	24.49	2.0	1.4	3.6	11.2	13.2
	50%	21.18	2.3	2.0	3.2	9.0	10.3	24.97	2.5	1.9	3.1	9.1	10.8	23.08	2.4	1.9	3.2	9.0	10.5
	0%	26.02	2.7	1.7	3.3	10.0	12.0	24.69	2.6	1.6	3.1	9.0	10.7	25.36	2.7	1.6	3.2	9.5	11.4
E7018 - 1 PLUS (Long Arc)	100%	24.78	2.7	1.5	4.2	9.0	10.8	21.37	1.8	1.6	3.5	10.4	12.3	23.07	2.2	1.6	3.9	9.7	11.6
	50%	18.75	1.8	1.6	3.1	9.5	11.5	18.30	1.7	1.3	3.6	9.8	11.9	18.52	1.8	1.4	3.3	9.7	11.7
	0%	22.11	2.1	1.7	3.3	9.1	11.1	17.41	1.7	1.3	3.2	9.3	10.8	19.76	1.9	1.5	3.2	9.2	11.0

Appendix II

Raw Data

SMAW Electrode Class: E6010 - 5P (Short Arc)

January 16, 2001

#1. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.9375	1.3750	61.0
2	13.9375	1.6250	58.0
3	13.9375	1.3750	61.7
			180.7

Current:	115 Amps		
Voltage:	24 Volts		
Wt. Base and Weld:	1213.2 grams	Wt. Electrodes:	76.2 grams
Wt. Base:	1159.3 grams	Wt. Stubs:	7.2 grams
Wt. Weld Metal:	53.9 grams	Wt. Consumed:	69.0 grams

Calculations:

Average Length Consumed:	12.479 inches	Deposition Efficiency:	78.1 %
Average Welding Time:	60.2 seconds	Absolute Welding Rate:	0.382 grams/second
Average Burning Rate:	0.207 inches/second	Deposition Rate:	0.298 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	30.2773	1.816	2.657	4.096	9.255	12.022
End (-1.5")	28.5537	1.771	2.646	4.046	9.185	11.285

#2. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	14.0000	1.7500	52.5
2	14.0000	1.3125	53.4
3	14.0625	1.2500	53.4
			159.4

Current:	115 Amps		
Voltage:	30 Volts		
Wt. Base and Weld:	1291.5 grams	Wt. Electrodes:	76.4 grams
Wt. Base:	1239.4 grams	Wt. Stubs:	7.0 grams
Wt. Weld Metal:	52.1 grams	Wt. Consumed:	69.4 grams

Calculations:

Average Length Consumed:	12.583 inches	Deposition Efficiency:	75.1 %
Average Welding Time:	53.1 seconds	Absolute Welding Rate:	0.435 grams/second
Average Burning Rate:	0.237 inches/second	Deposition Rate:	0.327 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	31.5699	1.381	2.696	4.703	9.944	12.986
End (-1.5")	32.3068	1.395	3.095	4.730	9.808	12.489

#3. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	14.0000	1.5625	47.8
2	14.0000	1.5625	47.0
3	14.0000	1.3125	48.7
			143.5

Current:	115 Amps		
Voltage:	32 Volts		
Wt. Base and Weld:	1245.7 grams	Wt. Electrodes:	76.2 grams
Wt. Base:	1199.4 grams	Wt. Stubs:	7.2 grams
Wt. Weld Metal:	46.3 grams	Wt. Consumed:	69.0 grams

Calculations:

Average Length Consumed:	12.521 inches	Deposition Efficiency:	67.1 %
Average Welding Time:	47.8 seconds	Absolute Welding Rate:	0.481 grams/second
Average Burning Rate:	0.262 inches/second	Deposition Rate:	0.323 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	35.4168	1.507	3.646	5.327	9.651	12.795
End (-1.5")	33.8727	1.341	3.719	5.223	9.023	12.559

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#4. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.9375	1.5000	61.1
2	13.9375	1.4375	60.0
3	13.9375	1.3125	60.8
			181.9

Current:	115 Amps		
Voltage:	24 Volts		
Wt. Base and Weld:	1265.3 grams	Wt. Electrodes:	79.5 grams
Wt. Base:	1209.0 grams	Wt. Stubs:	9.2 grams
Wt. Weld Metal:	56.3 grams	Wt. Consumed:	70.3 grams

Calculations:

Average Length Consumed:	12.521 inches	Deposition Efficiency:	80.1 %
Average Welding Time:	60.6 seconds	Absolute Welding Rate:	0.386 grams/second
Average Burning Rate:	0.207 inches/second	Deposition Rate:	0.310 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	24.2276	1.348	2.365	3.912	8.885	11.648
End (-1.5")	25.9977	1.381	2.721	3.976	9.313	11.804

#5. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.8750	1.5000	56.1
2	13.8750	1.5625	48.9
3	13.8750	3.5000	59.6
			164.7

Current:	115 Amps		
Voltage:	28 Volts		
Wt. Base and Weld:	1209.2 grams	Wt. Electrodes:	79.4 grams
Wt. Base:	1156.6 grams	Wt. Stubs:	14.9 grams
Wt. Weld Metal:	52.6 grams	Wt. Consumed:	64.5 grams

Calculations:

Average Length Consumed:	11.688 inches	Deposition Efficiency:	81.6 %
Average Welding Time:	54.9 seconds	Absolute Welding Rate:	0.392 grams/second
Average Burning Rate:	0.213 inches/second	Deposition Rate:	0.319 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	31.4089	1.831	2.537	4.435	10.789	12.090
End (-1.5")	27.6526	1.488	2.324	4.200	10.275	12.824

#6. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.8125	1.8125	55.3
2	13.8125	1.5625	54.7
3	13.8125	1.8125	55.8
			165.8

Current:	115 Amps		
Voltage:	26 Volts		
Wt. Base and Weld:	1265.8 grams	Wt. Electrodes:	79.2 grams
Wt. Base:	1209.4 grams	Wt. Stubs:	10.2 grams
Wt. Weld Metal:	56.4 grams	Wt. Consumed:	69.0 grams

Calculations:

Average Length Consumed:	12.083 inches	Deposition Efficiency:	81.7 %
Average Welding Time:	55.3 seconds	Absolute Welding Rate:	0.416 grams/second
Average Burning Rate:	0.219 inches/second	Deposition Rate:	0.340 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	29.9359	1.742	2.694	4.983	10.371	13.167
End (-1.5")	27.2989	1.542	2.498	4.170	10.013	12.381

#7. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.7500	1.6875	62.8
2	13.7500	1.8125	61.1
3	13.7500	1.9375	63.3
			187.2

Current: 115 Amps
Voltage: 24 Volts

Wt. Base and Weld:	1289.6 grams	Wt. Electrodes:	78.9 grams
Wt. Base:	1236.7 grams	Wt. Stubs:	9.6 grams
Wt. Weld Metal:	52.9 grams	Wt. Consumed:	69.3 grams

Calculations:

Average Length Consumed:	11.938 inches	Deposition Efficiency:	76.3 %
Average Welding Time:	62.4 seconds	Absolute Welding Rate:	0.370 grams/second
Average Burning Rate:	0.191 inches/second	Deposition Rate:	0.283 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	23.3729	1.580	2.414	3.577	8.999	11.172
End (-1.5")	24.9140	1.571	2.278	4.163	9.583	12.096

#8. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.8125	5.8125	36.7
2	13.8125	2.1875	51.0
3	13.8125	1.8750	51.8
			139.5

Current: 115 Amps
Voltage: 30 Volts

Wt. Base and Weld:	1201.2 grams	Wt. Electrodes:	78.9 grams
Wt. Base:	1161.7 grams	Wt. Stubs:	18.6 grams
Wt. Weld Metal:	39.5 grams	Wt. Consumed:	60.3 grams

Calculations:

Average Length Consumed:	10.521 inches	Deposition Efficiency:	65.5 %
Average Welding Time:	46.5 seconds	Absolute Welding Rate:	0.432 grams/second
Average Burning Rate:	0.226 inches/second	Deposition Rate:	0.283 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	23.9195	0.870	2.451	4.901	10.673	13.513
End (-1.5")	25.3225	1.587	2.231	4.413	9.000	12.273

#9. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.7500	1.5625	47.6
2	13.7500	1.8125	47.3
3	13.7500	1.8125	46.8
			141.8

Current: 115 Amps
Voltage: 30 Volts

Wt. Base and Weld:	1243.7 grams	Wt. Electrodes:	79.0 grams
Wt. Base:	1204.3 grams	Wt. Stubs:	9.2 grams
Wt. Weld Metal:	39.4 grams	Wt. Consumed:	69.8 grams

Calculations:

Average Length Consumed:	12.021 inches	Deposition Efficiency:	56.4 %
Average Welding Time:	47.3 seconds	Absolute Welding Rate:	0.492 grams/second
Average Burning Rate:	0.254 inches/second	Deposition Rate:	0.278 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	30.9303	1.488	3.507	5.473	8.236	13.019
End (-1.5")	25.8600	1.887	2.524	4.337	8.479	10.978

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#10. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.7500	1.9375	59.9
2	13.7500	2.1250	59.9
3	13.7500	1.6250	64.2
			184.0

Current: 115 Amps
Voltage: 30 Volts

Wt. Base and Weld:	1597.8 grams	Wt. Electrodes:	79.6 grams
Wt. Base:	1549.4 grams	Wt. Stubs:	10.2 grams
Wt. Weld Metal:	48.4 grams	Wt. Consumed:	69.4 grams

Calculations:

Average Length Consumed:	11.854 inches	Deposition Efficiency:	69.7 %
Average Welding Time:	61.3 seconds	Absolute Welding Rate:	0.377 grams/second
Average Burning Rate:	0.193 inches/second	Deposition Rate:	0.263 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	31.3358	1.557	3.352	5.463	8.682	13.038
End (-1.5")	33.2527	1.674	3.273	5.198	9.071	11.820

#11. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.6875	1.9375	53.2
2	13.6875	1.7500	54.3
3	13.6875	1.6875	53.4
			160.9

Current: 115 Amps
Voltage: 40 Volts

Wt. Base and Weld:	1568.6 grams	Wt. Electrodes:	79.3 grams
Wt. Base:	1519.8 grams	Wt. Stubs:	9.8 grams
Wt. Weld Metal:	48.8 grams	Wt. Consumed:	69.5 grams

Calculations:

Average Length Consumed:	11.896 inches	Deposition Efficiency:	70.2 %
Average Welding Time:	53.6 seconds	Absolute Welding Rate:	0.432 grams/second
Average Burning Rate:	0.222 inches/second	Deposition Rate:	0.303 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	37.8899	1.707	3.217	5.122	10.615	13.709
End (-1.5")	40.4104	1.427	3.429	5.131	11.689	14.592

#12. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.6875	1.9375	47.7
2	13.6875	1.5625	50.3
3	13.6875	1.6250	50.7
			148.7

Current: 115 Amps
Voltage: 38 Volts

Wt. Base and Weld:	1533.9 grams	Wt. Electrodes:	79.1 grams
Wt. Base:	1489.8 grams	Wt. Stubs:	8.8 grams
Wt. Weld Metal:	44.1 grams	Wt. Consumed:	70.3 grams

Calculations:

Average Length Consumed:	11.979 inches	Deposition Efficiency:	62.7 %
Average Welding Time:	49.6 seconds	Absolute Welding Rate:	0.473 grams/second
Average Burning Rate:	0.242 inches/second	Deposition Rate:	0.297 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	44.6502	2.062	3.751	6.633	10.905	14.309
End (-1.5")	43.2384	1.776	3.924	6.151	10.578	14.238

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#13. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	17.6250	2.1250	87.4
2	17.6250	2.0625	84.1
3	17.6250	2.1875	85.0
			256.5

Current: 115 Amps
Voltage: 22 Volts

Wt. Base and Weld:	1587.1 grams	Wt. Electrodes:	119.1 grams
Wt. Base:	1511.1 grams	Wt. Stubs:	12.6 grams
Wt. Weld Metal:	76.0 grams	Wt. Consumed:	106.5 grams

Calculations:

Average Length Consumed:	15.500 inches	Deposition Efficiency:	71.4 %
Average Welding Time:	85.5 seconds	Absolute Welding Rate:	0.415 grams/second
Average Burning Rate:	0.181 inches/second	Deposition Rate:	0.296 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	21.0965	2.187	1.659	2.740	9.176	10.483
End (-1.5")	19.3989	2.413	1.081	2.388	9.604	10.684

#14. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	17.6875	2.1250	89.2
2	17.6875	1.6875	90.8
3	17.6875	2.4375	90.5
			270.5

Current: 115 Amps
Voltage: 22 Volts

Wt. Base and Weld:	1602.8 grams	Wt. Electrodes:	119.1 grams
Wt. Base:	1526.1 grams	Wt. Stubs:	12.3 grams
Wt. Weld Metal:	76.7 grams	Wt. Consumed:	106.8 grams

Calculations:

Average Length Consumed:	15.604 inches	Deposition Efficiency:	71.8 %
Average Welding Time:	90.2 seconds	Absolute Welding Rate:	0.395 grams/second
Average Burning Rate:	0.173 inches/second	Deposition Rate:	0.284 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	18.8002	2.115	1.344	2.588	8.784	10.029
End (-1.5")	19.8710	2.469	1.521	2.743	7.407	9.403

#15. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	17.6875	1.9375	91.1
2	17.6875	2.5625	89.9
3	17.6875	1.6250	92.5
			273.5

Current: 115 Amps
Voltage: 20 Volts

Wt. Base and Weld:	1631.9 grams	Wt. Electrodes:	119.2 grams
Wt. Base:	1555.4 grams	Wt. Stubs:	11.9 grams
Wt. Weld Metal:	76.5 grams	Wt. Consumed:	107.3 grams

Calculations:

Average Length Consumed:	15.646 inches	Deposition Efficiency:	71.3 %
Average Welding Time:	91.2 seconds	Absolute Welding Rate:	0.392 grams/second
Average Burning Rate:	0.172 inches/second	Deposition Rate:	0.280 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	15.0111	2.220	1.072	2.918	7.033	8.754
End (-1.5")	15.5280	2.593	0.840	2.840	7.261	9.335

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#16. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	17.6250	2.0625	87.4
2	17.6250	2.8750	84.1
3	17.6250	2.1250	85.0
			256.5

Current: 115 Amps
Voltage: 28 Volts

Wt. Base and Weld:	1127.5 grams	Wt. Electrodes:	118.8 grams
Wt. Base:	1051.3 grams	Wt. Stubs:	13.1 grams
Wt. Weld Metal:	76.2 grams	Wt. Consumed:	105.7 grams

Calculations:

Average Length Consumed:	15.271 inches	Deposition Efficiency:	72.1 %
Average Welding Time:	85.5 seconds	Absolute Welding Rate:	0.412 grams/second
Average Burning Rate:	0.179 inches/second	Deposition Rate:	0.297 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	18.9461	1.881	1.385	3.527	9.014	11.496
End (-1.5")	18.5679	1.658	1.213	3.811	9.576	11.828

#17. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	17.6875	1.9375	89.2
2	17.6875	1.9375	90.8
3	17.6875	1.5625	90.5
			270.5

Current: 115 Amps
Voltage: 30 Volts

Wt. Base and Weld:	1123.9 grams	Wt. Electrodes:	119.6 grams
Wt. Base:	1047.6 grams	Wt. Stubs:	12.0 grams
Wt. Weld Metal:	76.3 grams	Wt. Consumed:	107.6 grams

Calculations:

Average Length Consumed:	15.875 inches	Deposition Efficiency:	70.9 %
Average Welding Time:	90.2 seconds	Absolute Welding Rate:	0.398 grams/second
Average Burning Rate:	0.176 inches/second	Deposition Rate:	0.282 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	16.7593	2.256	0.992	3.124	9.149	10.785
End (-1.5")	14.1185	1.792	1.212	3.054	8.506	10.752

#18. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	17.6875	1.8125	91.1
2	17.6875	2.8750	89.9
3	17.6875	1.5625	92.5
			273.5

Current: 115 Amps
Voltage: 22 Volts

Wt. Base and Weld:	1122.4 grams	Wt. Electrodes:	119.2 grams
Wt. Base:	1045.4 grams	Wt. Stubs:	11.3 grams
Wt. Weld Metal:	77.0 grams	Wt. Consumed:	107.9 grams

Calculations:

Average Length Consumed:	15.604 inches	Deposition Efficiency:	71.4 %
Average Welding Time:	91.2 seconds	Absolute Welding Rate:	0.395 grams/second
Average Burning Rate:	0.171 inches/second	Deposition Rate:	0.282 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	14.4916	2.187	1.054	3.135	7.166	9.748
End (-1.5")	16.8414	2.136	1.267	2.782	7.229	9.241

#19. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.7500	1.5000	87.4
2	13.7500	1.6250	84.1
3	13.7500	1.5000	85.0
			256.5

Current: 135 Amps
Voltage: 20 Volts

Wt. Base and Weld:	1124.4 grams	Wt. Electrodes:	108.1 grams
Wt. Base:	1052.2 grams	Wt. Stubs:	11.2 grams
Wt. Weld Metal:	72.2 grams	Wt. Consumed:	96.9 grams

Calculations:

Average Length Consumed:	12.208 inches	Deposition Efficiency:	74.5 %
Average Welding Time:	85.5 seconds	Absolute Welding Rate:	0.378 grams/second
Average Burning Rate:	0.143 inches/second	Deposition Rate:	0.282 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	24.4349	1.963	1.515	3.875	11.378	13.514
End (-1.5")	24.5480	2.090	1.349	3.334	10.953	12.911

#20. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.7500	1.6250	89.2
2	13.7500	1.8125	90.8
3	13.7500	1.5000	90.5
			270.5

Current: 132 Amps
Voltage: 24 Volts

Wt. Base and Weld:	1123.6 grams	Wt. Electrodes:	108.6 grams
Wt. Base:	1052.3 grams	Wt. Stubs:	12.2 grams
Wt. Weld Metal:	71.3 grams	Wt. Consumed:	96.4 grams

Calculations:

Average Length Consumed:	12.104 inches	Deposition Efficiency:	74.0 %
Average Welding Time:	90.2 seconds	Absolute Welding Rate:	0.356 grams/second
Average Burning Rate:	0.134 inches/second	Deposition Rate:	0.264 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	21.1766	2.297	1.951	3.235	8.965	10.274
End (-1.5")	24.9745	2.534	1.870	3.124	9.053	10.800

#21. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.8125	1.6875	91.1
2	13.8125	1.8750	89.9
3	13.8125	1.7500	92.5
			273.5

Current: 135 Amps
Voltage: 20 Volts

Wt. Base and Weld:	1123.0 grams	Wt. Electrodes:	109.2 grams
Wt. Base:	1052.2 grams	Wt. Stubs:	13.1 grams
Wt. Weld Metal:	70.8 grams	Wt. Consumed:	96.1 grams

Calculations:

Average Length Consumed:	12.042 inches	Deposition Efficiency:	73.7 %
Average Welding Time:	91.2 seconds	Absolute Welding Rate:	0.351 grams/second
Average Burning Rate:	0.132 inches/second	Deposition Rate:	0.259 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	26.0205	2.724	1.674	3.274	10.021	12.020
End (-1.5")	24.6929	2.648	1.584	3.118	8.982	10.715

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#22. Polarity: DC ELECTRODE POSITIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.8125	2.1250	87.4
2	13.8125	1.9375	84.1
3	13.8125	1.8750	85.0
			256.5

Current: 135 Amps
Voltage: 22 Volts

Wt. Base and Weld:	1114.5 grams	Wt. Electrodes:	108.7 grams
Wt. Base:	1047.9 grams	Wt. Stubs:	14.7 grams
Wt. Weld Metal:	66.6 grams	Wt. Consumed:	94.0 grams

Calculations:

Average Length Consumed:	11.833 inches	Deposition Efficiency:	70.9 %
Average Welding Time:	85.5 seconds	Absolute Welding Rate:	0.367 grams/second
Average Burning Rate:	0.138 inches/second	Deposition Rate:	0.260 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	24.7803	2.703	1.537	4.240	8.951	10.810
End (-1.5")	21.3652	1.773	1.625	3.545	10.439	12.310

#23. Polarity: AC 50/50

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.8125	1.8750	89.2
2	13.8125	1.6250	90.8
3	13.8125	1.8750	90.5
			270.5

Current: 133 Amps
Voltage: 22 Volts

Wt. Base and Weld:	1119.3 grams	Wt. Electrodes:	109.2 grams
Wt. Base:	1049.8 grams	Wt. Stubs:	13.2 grams
Wt. Weld Metal:	69.5 grams	Wt. Consumed:	96.0 grams

Calculations:

Average Length Consumed:	12.021 inches	Deposition Efficiency:	72.4 %
Average Welding Time:	90.2 seconds	Absolute Welding Rate:	0.355 grams/second
Average Burning Rate:	0.133 inches/second	Deposition Rate:	0.257 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	18.7502	1.782	1.562	3.100	9.544	11.546
End (-1.5")	18.2971	1.732	1.262	3.588	9.849	11.902

#24. Polarity: DC ELECTRODE NEGATIVE

Pass	Initial Length (inches)	Final Length (inches)	Time (seconds)
1	13.7500	2.1250	91.1
2	13.7500	1.9375	89.9
3	13.7500	1.7500	92.5
			273.5

Current: 135 Amps
Voltage: 22 Volts

Wt. Base and Weld:	1115.2 grams	Wt. Electrodes:	108.8 grams
Wt. Base:	1049.5 grams	Wt. Stubs:	14.2 grams
Wt. Weld Metal:	65.7 grams	Wt. Consumed:	94.6 grams

Calculations:

Average Length Consumed:	11.813 inches	Deposition Efficiency:	69.5 %
Average Welding Time:	91.2 seconds	Absolute Welding Rate:	0.346 grams/second
Average Burning Rate:	0.130 inches/second	Deposition Rate:	0.240 grams/second

Macrostructure Features:

Weld Section Position	Weld Area (mm^2)	Crown Height (mm)	Penetration Depth (mm)	HAZ Depth (mm)	Weld Width (mm)	HAZ Width (mm)
Start (+1.5")	22.1090	2.063	1.747	3.252	9.150	11.140
End (-1.5")	17.4060	1.733	1.318	3.173	9.276	10.765

Appendix III

Macrostructures

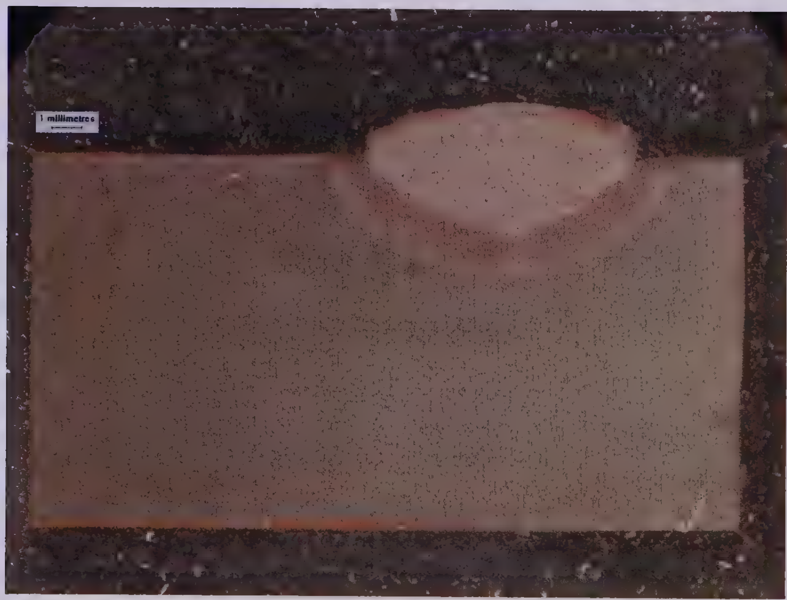

FIGURE 8. – Macrostructure of E6010-5P electrode on DC Electrode Positive; Section 1.5" from Start of Weld (Test #1 – Short Arc)

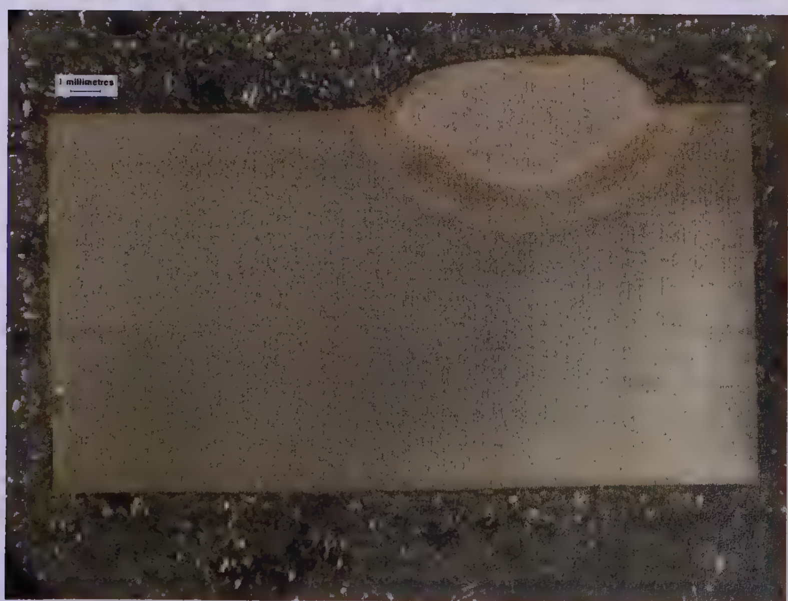

FIGURE 9. – Macrostructure of E6010-5P electrode on DC Electrode Positive; Section 1.5" from End of Weld (Test #1 – Short Arc)

FIGURE 10. – Macrostructure of E6010-5P electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #2 – Short Arc)

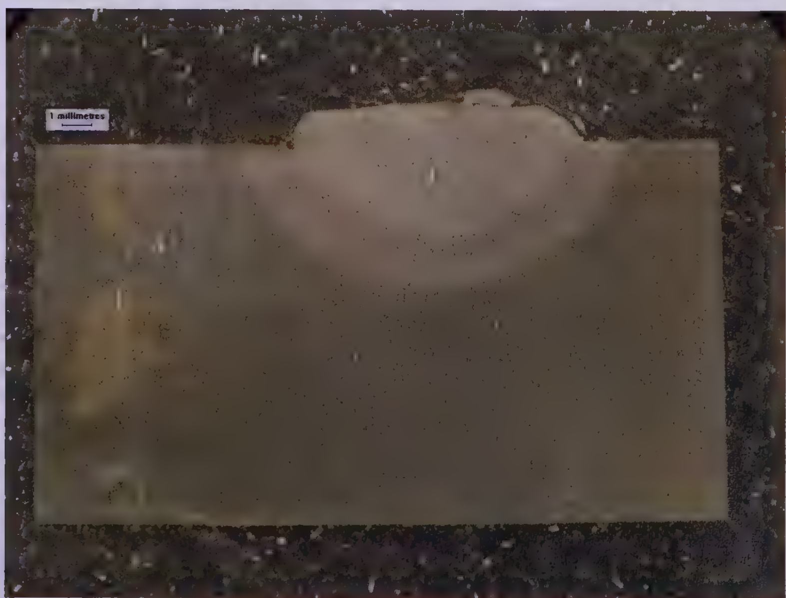

FIGURE 11. – Macrostructure of E6010-5P electrode on AC 50/50; Section 1.5″ from End of Weld (Test #2 – Short Arc)

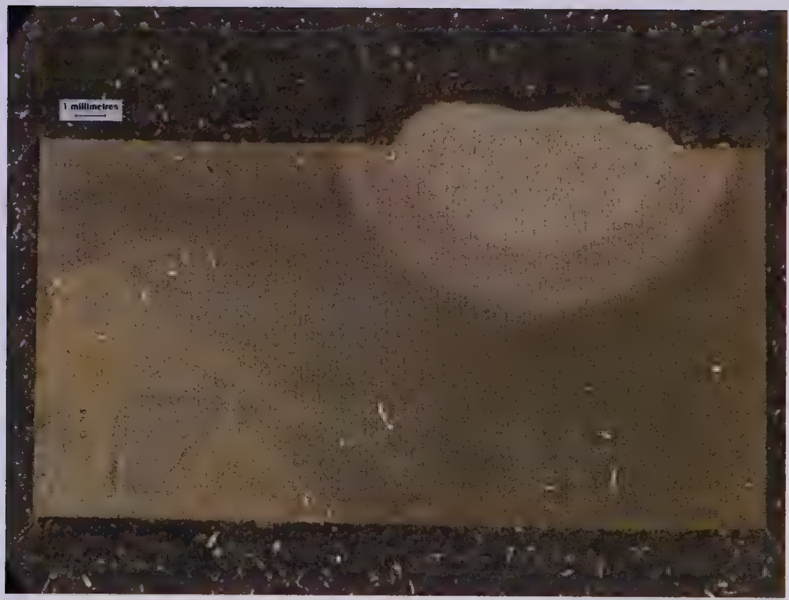

FIGURE 12. – Macrostructure of E6010-5P electrode on DC Electrode Negative Section 1.5" from Start of Weld (Test #3 – Short Arc)

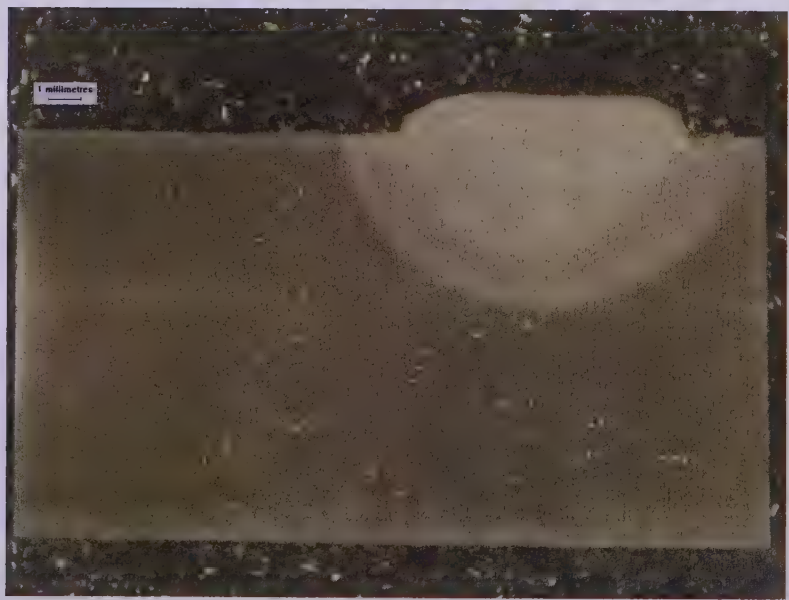

FIGURE 13. – Macrostructure of E6010-5P electrode on DC Electrode Negative Section 1.5" from End of Weld (Test #3 – Short Arc)

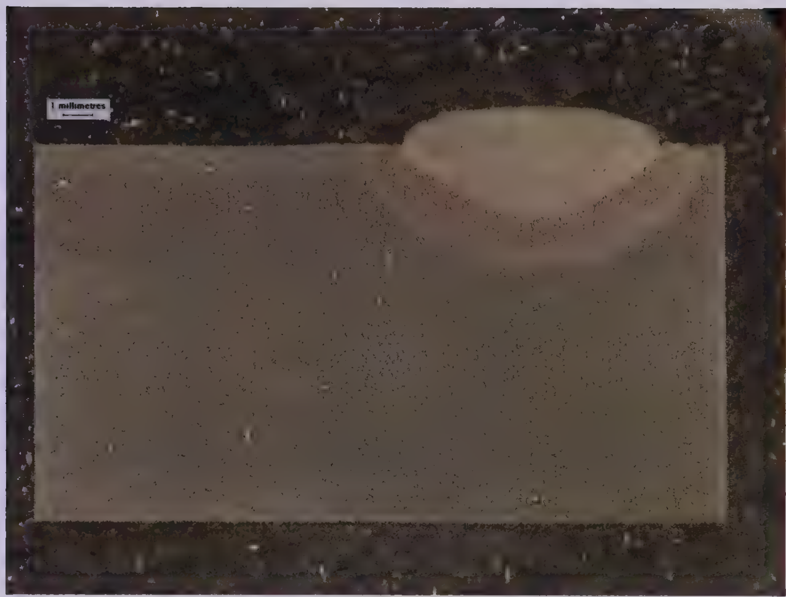

FIGURE 14. – Macrostructure of E6010-5P+ electrode on DC Electrode Positive; Section 1.5″ from Start of Weld (Test #4 – Short Arc)

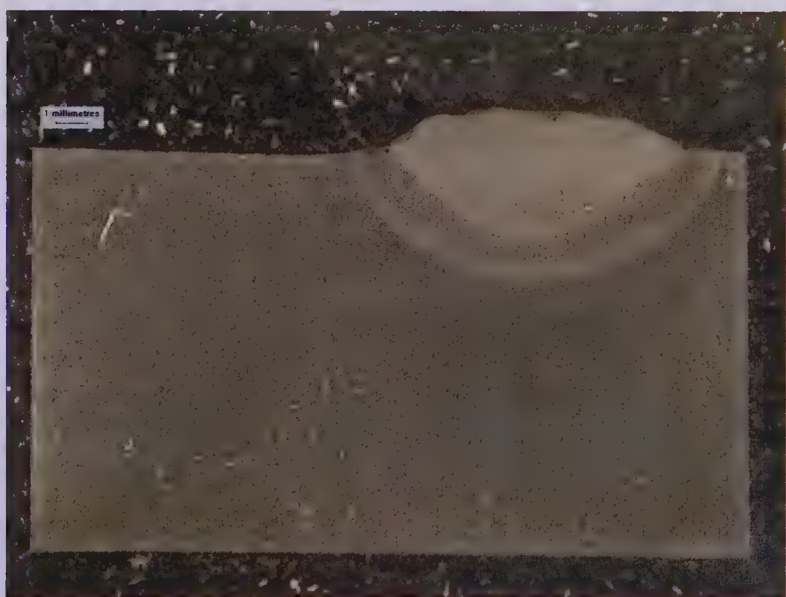

FIGURE 15. – Macrostructure of E6010-5P+ electrode on DC Electrode Positive; Section 1.5″ from End of Weld (Test #4 – Short Arc)

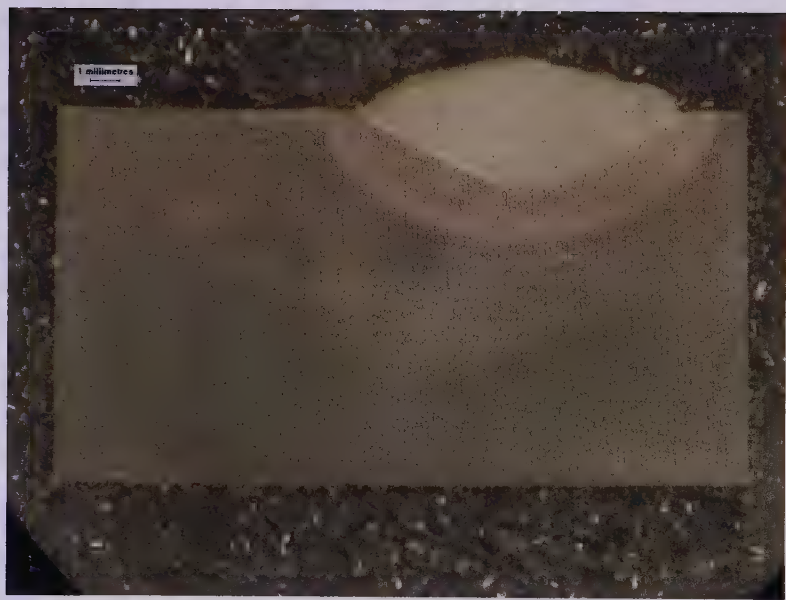

FIGURE 16. – Macrostructure of E6010-5P+ electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #5 – Short Arc)

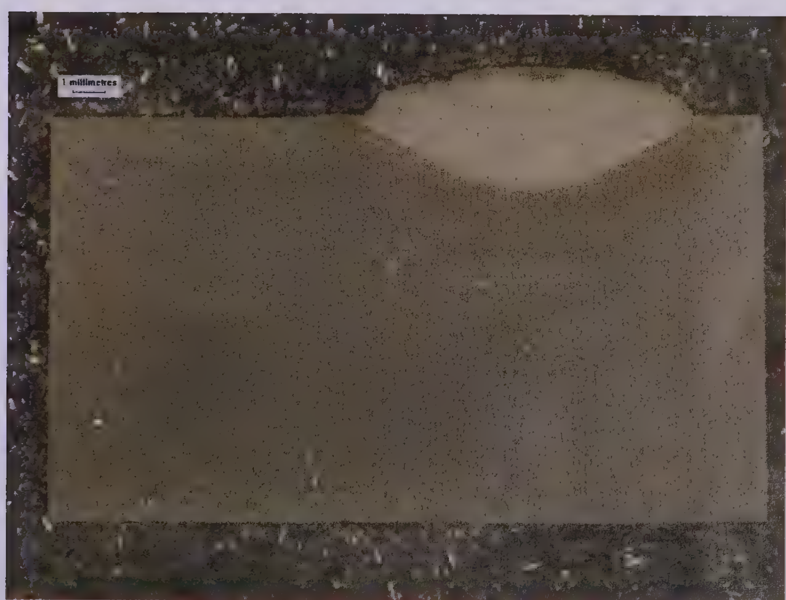

FIGURE 17. – Macrostructure of E6010-5P+ electrode on AC 50/50; Section 1.5″ from End of Weld (Test #5 – Short Arc)

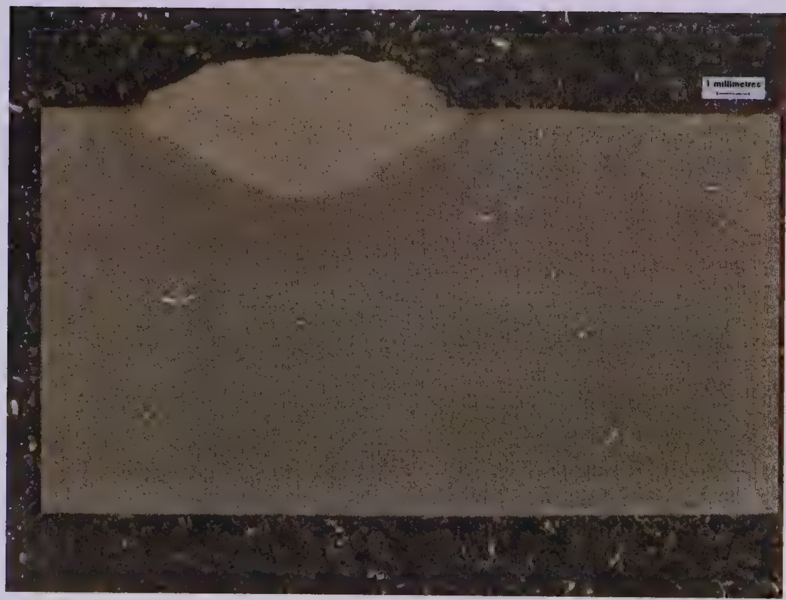

FIGURE 18. – Macrostructure of E6010-5P+ electrode on DC Electrode Negative; Section 1.5" from Start of Weld (Test #6 – Short Arc)

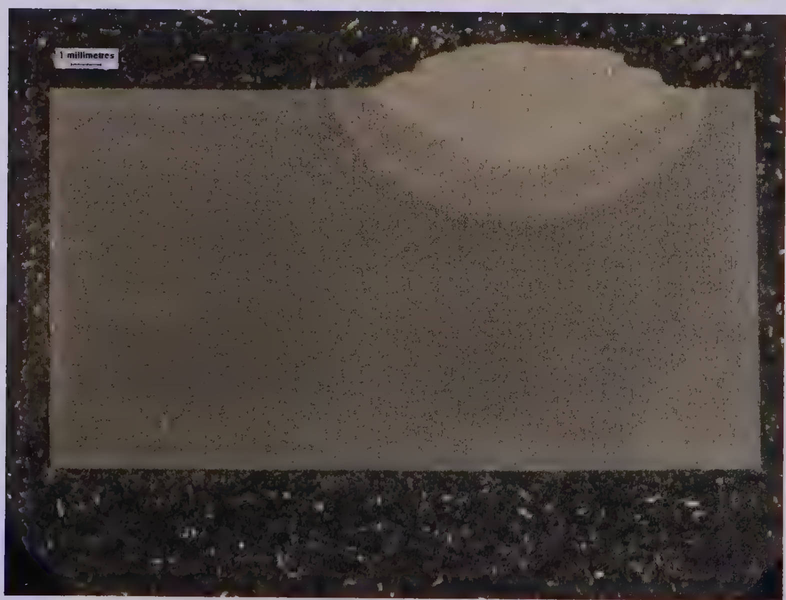

FIGURE 19. – Macrostructure of E6010-5P+ electrode on DC Electrode Negative; Section 1.5" from End of Weld (Test #6 – Short Arc)

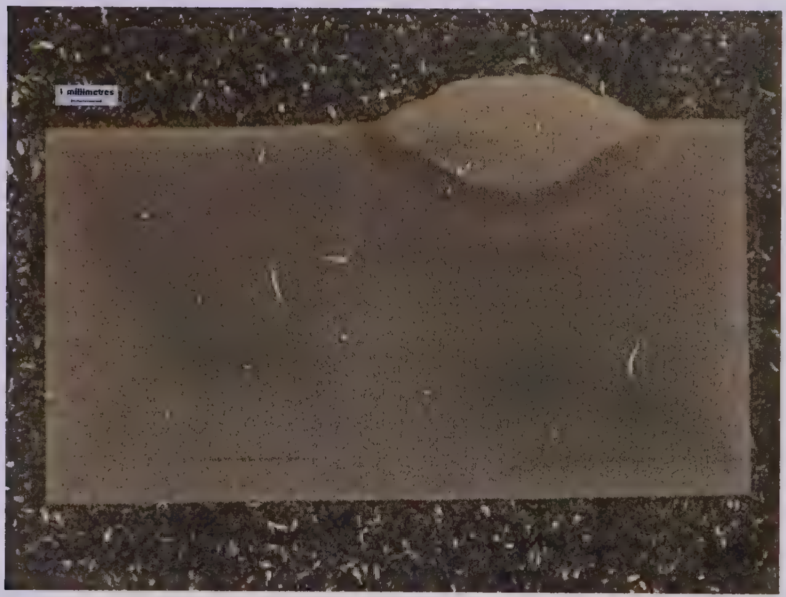

FIGURE 20. – Macrostructure of CSA E6010 LA ULTRA 10 electrode on DC Electrode Positive; Section 1.5″ from Start of Weld (Test #7 – Short Arc)

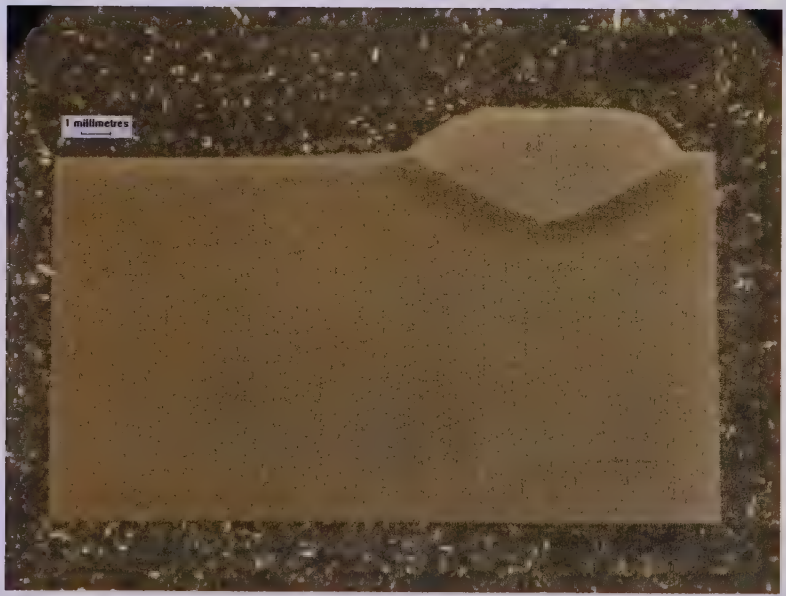

FIGURE 21. – Macrostructure of CSA E6010 LA ULTRA 10 electrode on DC Electrode Positive; Section 1.5″ from End of Weld (Test #7 – Short Arc)

FIGURE 22. – Macrostructure of CSA E6010 LA ULTRA 10 electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #8 – Short Arc)

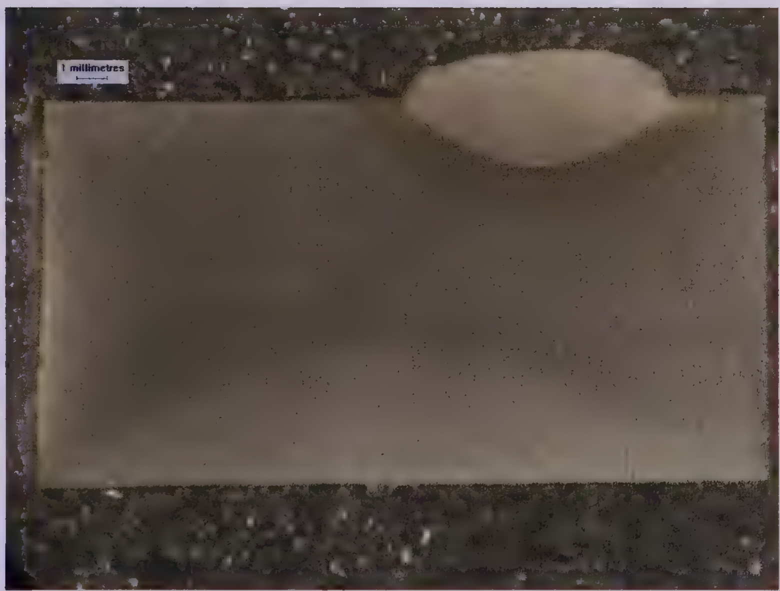

FIGURE 23. – Macrostructure of CSA E6010 LA ULTRA 10 electrode on AC 50/50; Section 1.5″ from End of Weld (Test #8 – Short Arc)

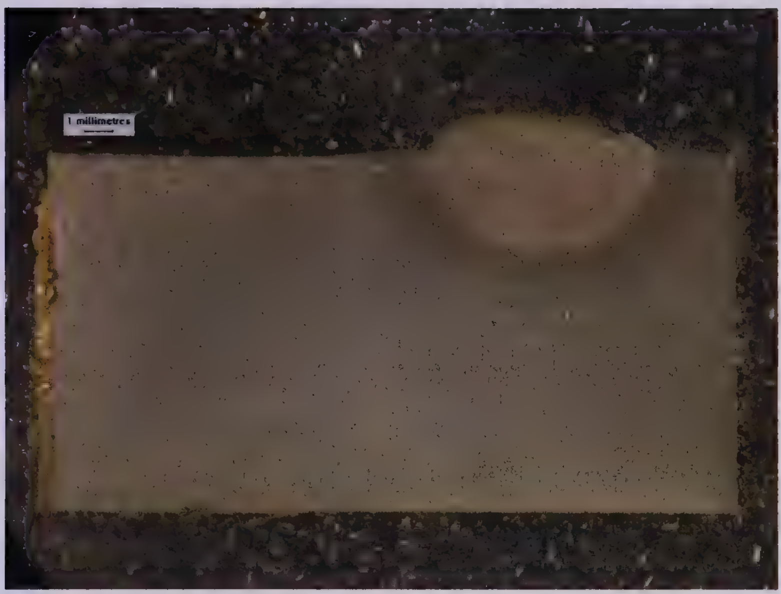

FIGURE 24. – Macrostructure of CSA E6010 LA ULTRA 10 electrode on DC Electrode Negative; Section 1.5″ from Start of Weld (Test #9 – Short Arc)

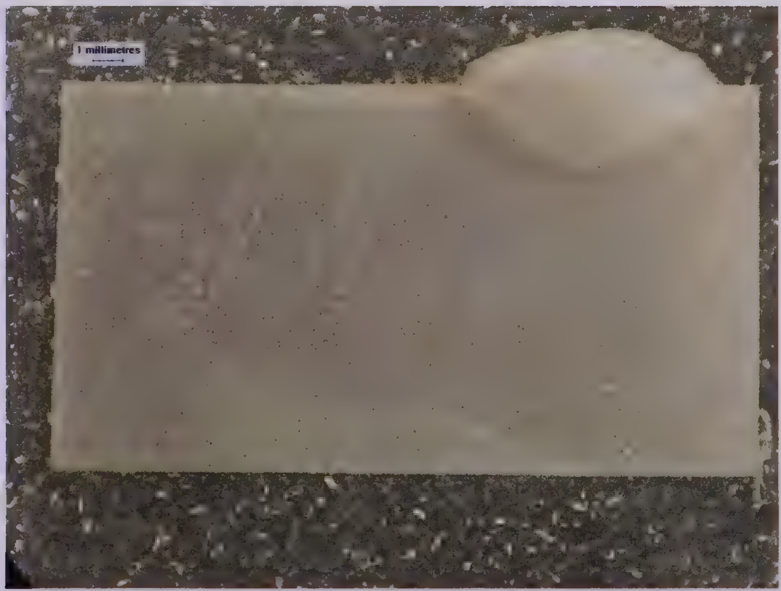

FIGURE 25. – Macrostructure of CSA E6010 LA ULTRA 10 electrode on DC Electrode Negative; Section 1.5″ from End of Weld (Test #9 – Short Arc)

FIGURE 26. – Macrostructure of CLA E6010X electrode on DC Electrode Positive; Section 1.5" from Start of Weld (Test #10 – Short Arc)

FIGURE 27. – Macrostructure of CLA E6010X electrode on DC Electrode Positive; Section 1.5" from End of Weld (Test #10 – Short Arc)

FIGURE 28. – Macrostructure of CLA E6010X electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #11 – Short Arc)

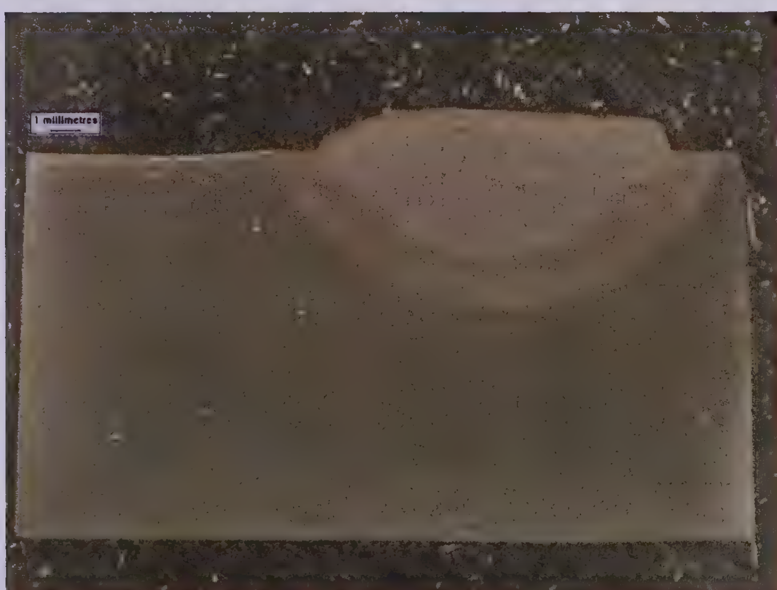

FIGURE 29. – Macrostructure of CLA E6010X electrode on AC 50/50; Section 1.5″ from End of Weld (Test #11 – Short Arc)

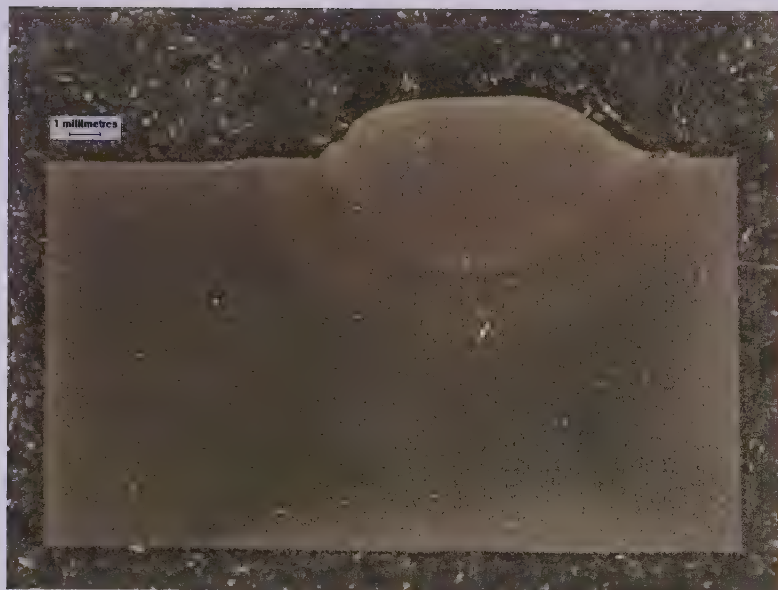

FIGURE 30. – Macrostructure of CLA E6010X electrode on DC Electrode Negative; Section 1.5" from Start of Weld (Test #12 – Short Arc)

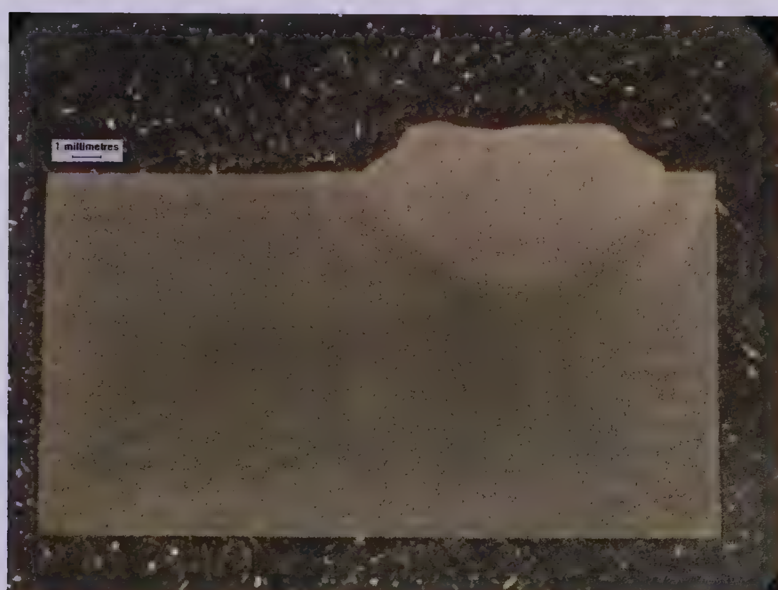

FIGURE 31. – Macrostructure of CLA E6010X electrode on DC Electrode Negative; Section 1.5" from End of Weld (Test #12 – Short Arc)

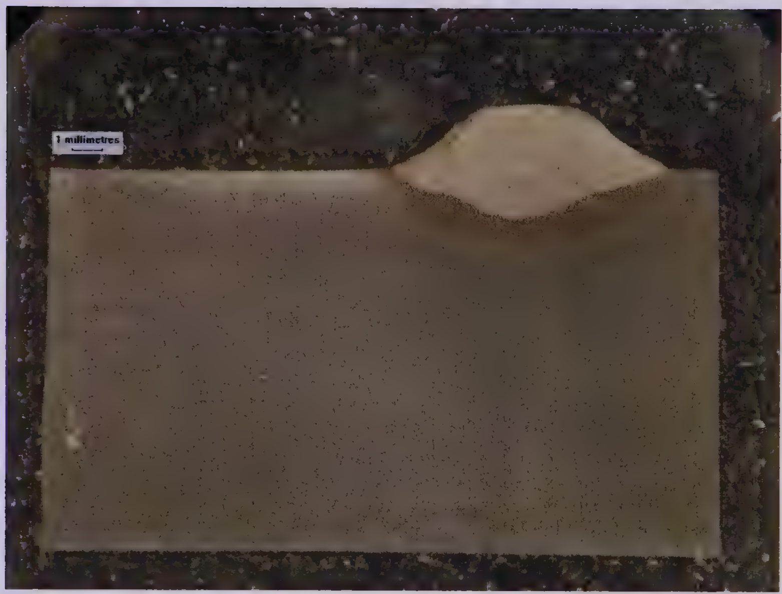

FIGURE 32. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Positive; Section 1.5″ from Start of Weld
(Test #13 – Short Arc)

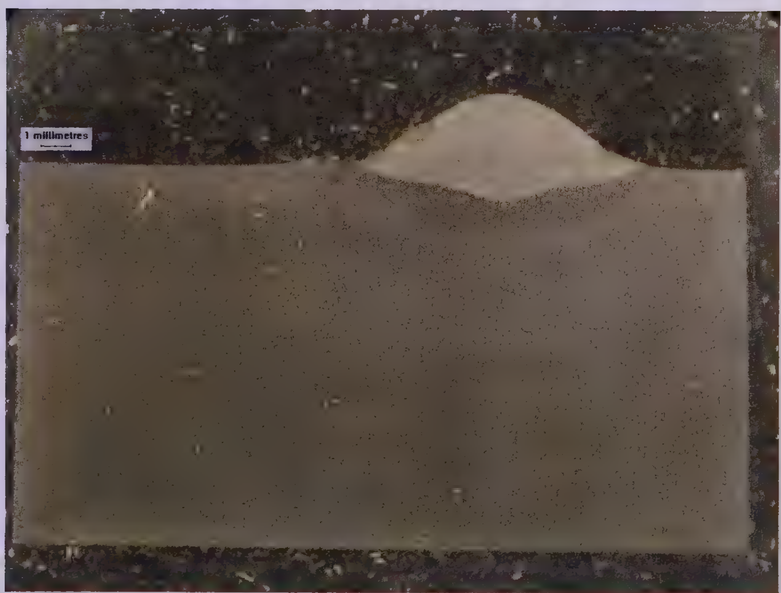

FIGURE 33. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Positive; Section 1.5″ from End of Weld
(Test #13 – Short Arc)

FIGURE 34. – Macrostructure of FRX E7016 – 1Ni electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #14 – Short Arc)

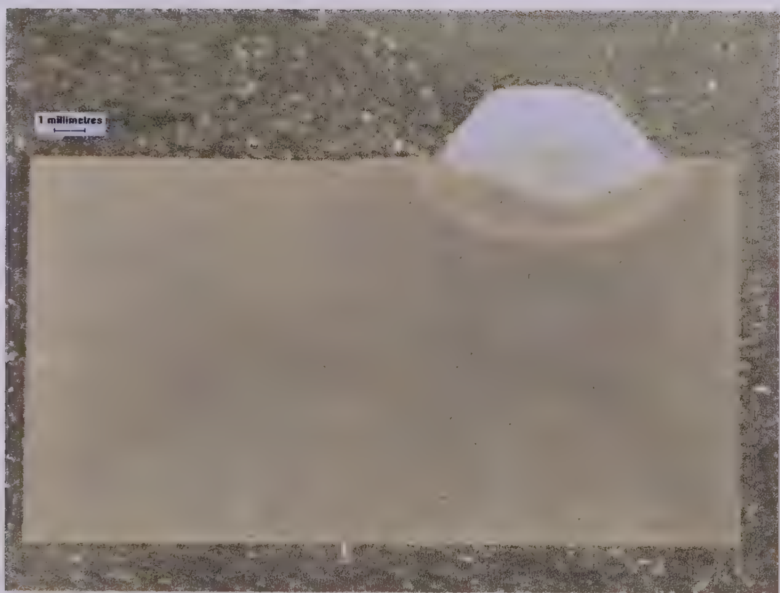

FIGURE 35. – Macrostructure of FRX E7016 – 1Ni electrode on AC 50/50; Section 1.5″ from End of Weld (Test #14 – Short Arc)

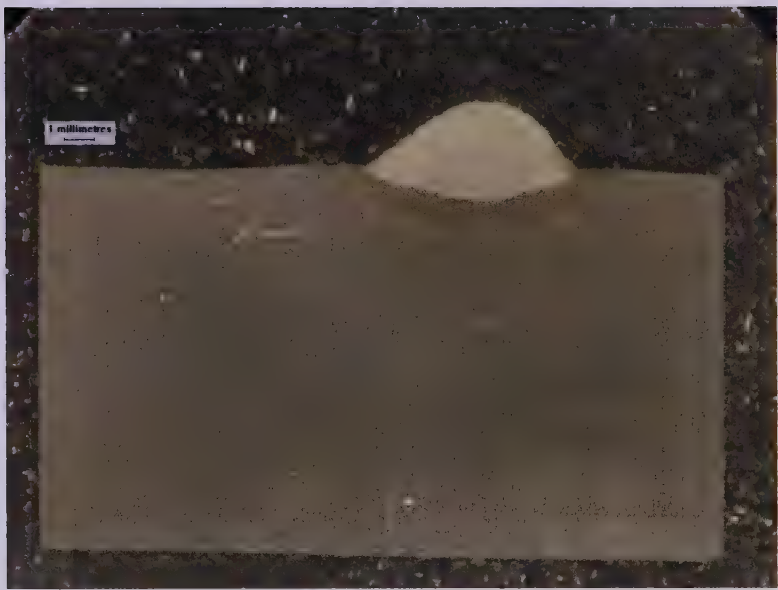

FIGURE 36. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Negative; Section 1.5″ from Start of Weld (Test #15 – Short Arc)

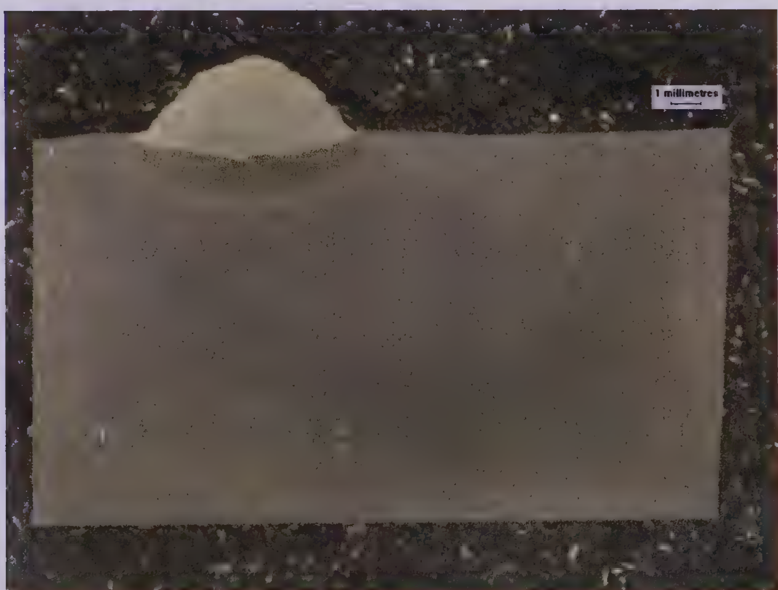

FIGURE 37. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Negative; Section 1.5″ from End of Weld (Test #15 – Short Arc)

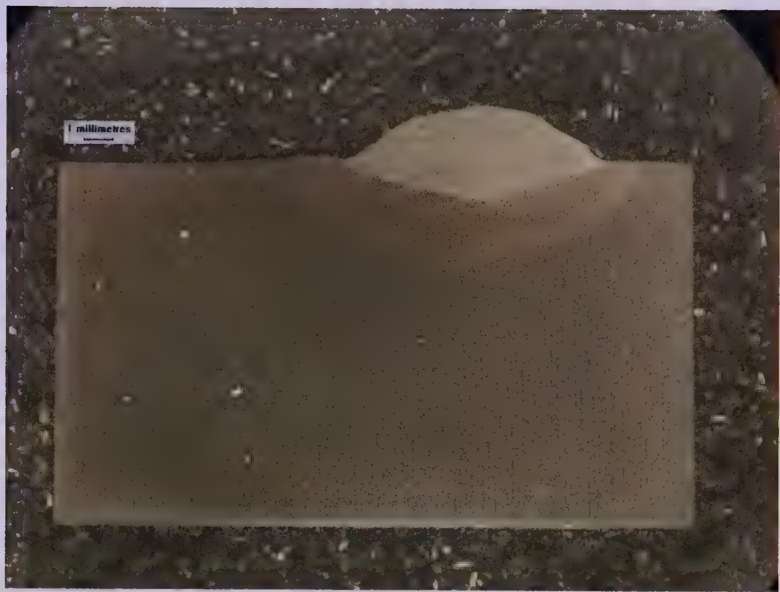

FIGURE 38. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Positive; Section 1.5″ from Start of Weld (Test #16 – Long Arc)

FIGURE 39. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Positive; Section 1.5″ from End of Weld (Test #16 – Long Arc)

FIGURE 40. – Macrostructure of FRX E7016 – 1Ni electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #17 – Long Arc)

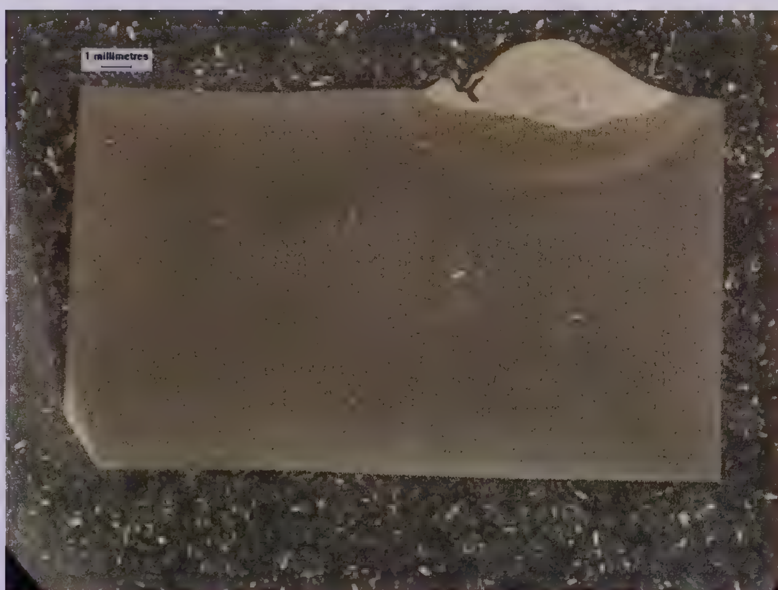

FIGURE 41. – Macrostructure of FRX E7016 – 1Ni electrode on AC 50/50; Section 1.5″ from End of Weld (Test #17 – Long Arc)

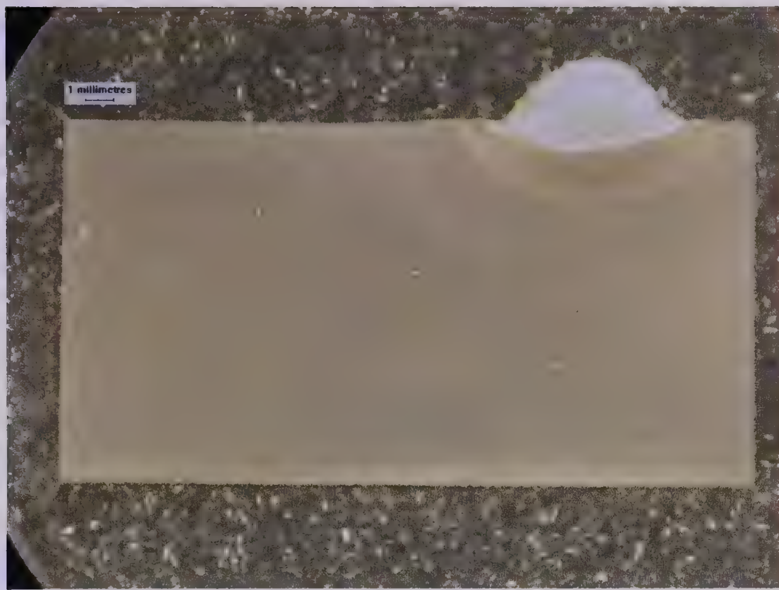

FIGURE 42. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Negative; Section 1.5″ from Start of Weld (Test #18 – Long Arc)

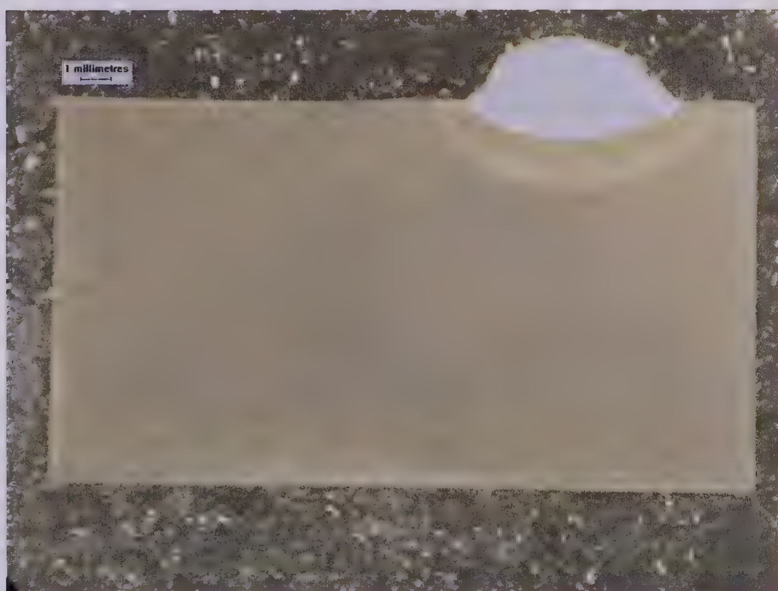

FIGURE 43. – Macrostructure of FRX E7016 – 1Ni electrode on DC Electrode Negative; Section 1.5″ from End of Weld (Test #18 – Long Arc)

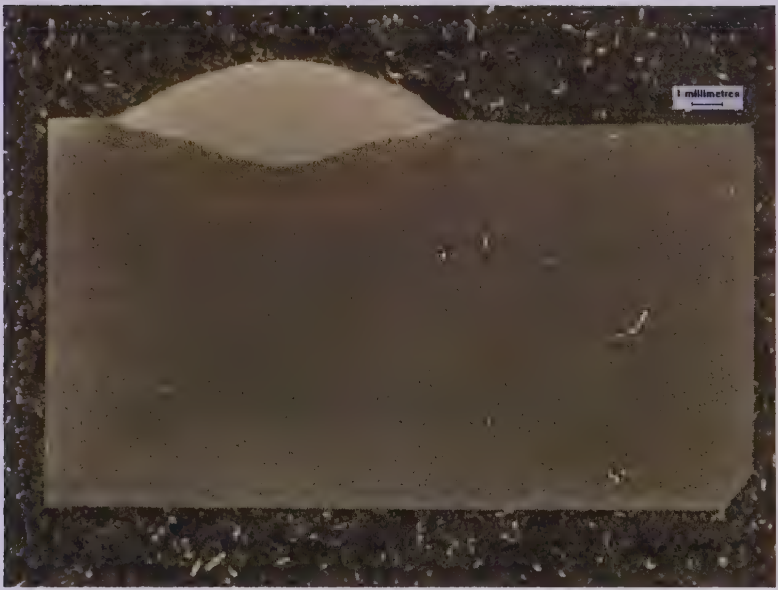

FIGURE 44. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Positive; Section 1.5″ from Start of Weld
(Test #19 – Short Arc)

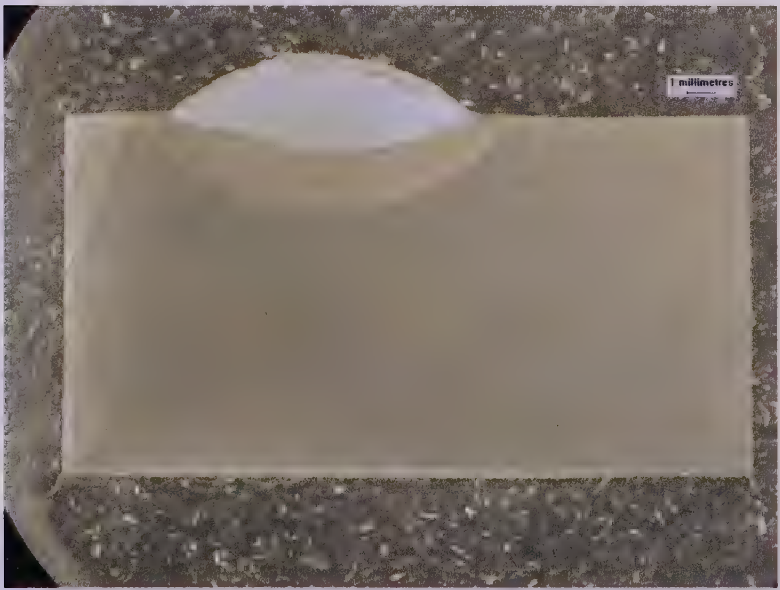

FIGURE 45. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Positive; Section 1.5″ from End of Weld
(Test #19 – Short Arc)

FIGURE 46. – Macrostructure of E7018 – 1 PLUS electrode on AC 50/50; Section 1.5″ from Start of Weld (Test #20 – Short Arc)

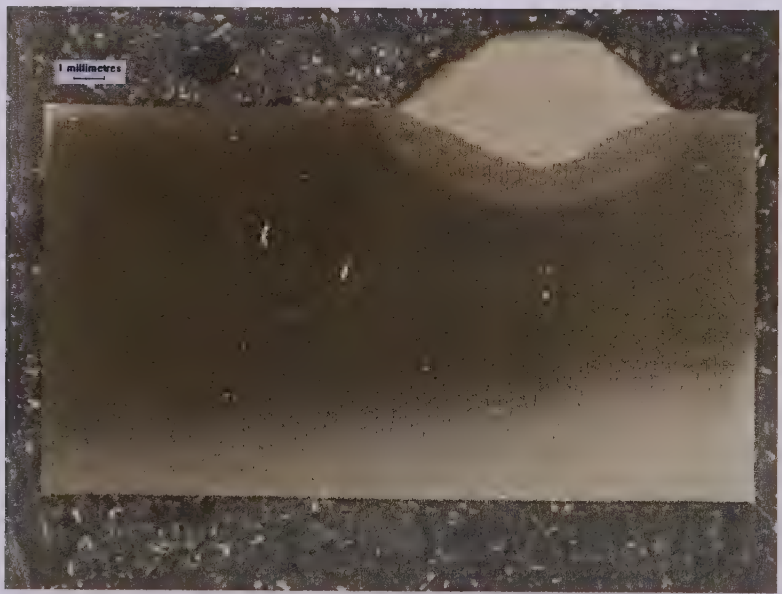

FIGURE 47. – Macrostructure of E7018 – 1 PLUS electrode on AC 50/50; Section 1.5″ from End of Weld (Test #20 – Short Arc)

FIGURE 48. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Negative; Section 1.5" from Start of Weld (Test #21 – Short Arc)

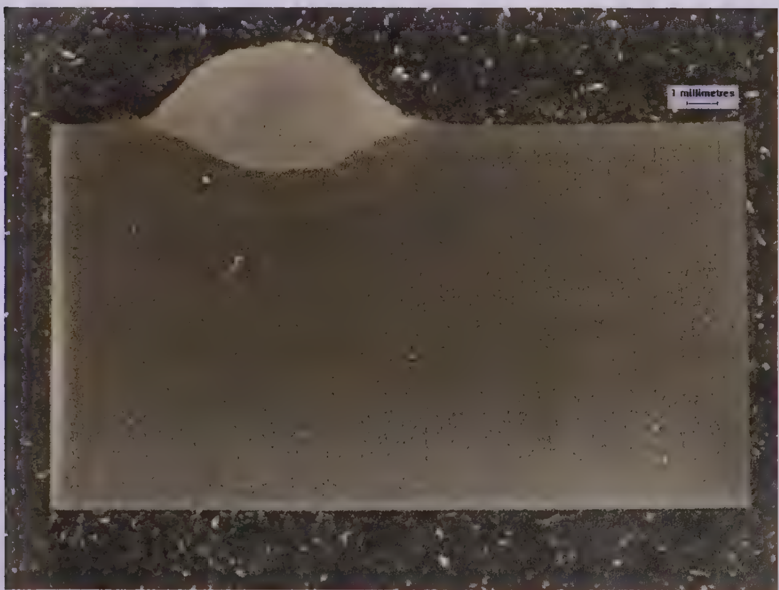

FIGURE 49. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Negative; Section 1.5" from End of Weld (Test #21 – Short Arc)

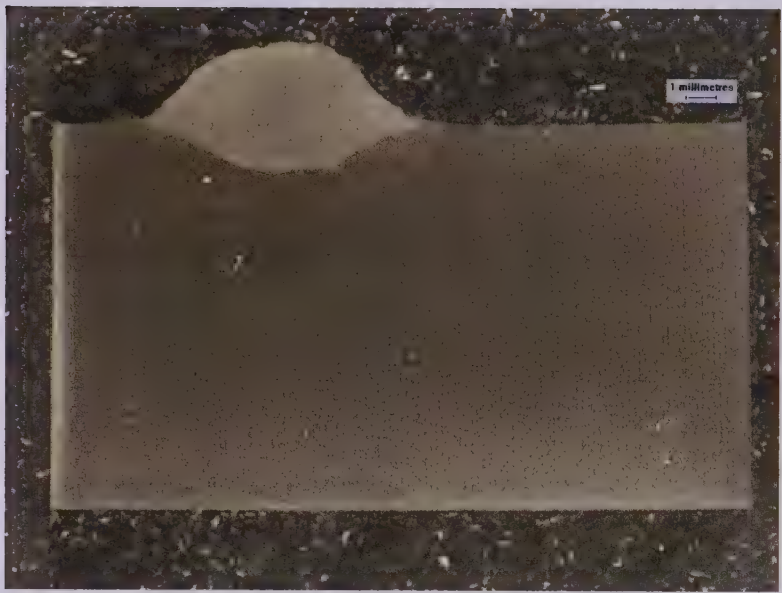

FIGURE 50. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Positive; Section 1.5″ from Start of Weld (Test #22 – Long Arc)

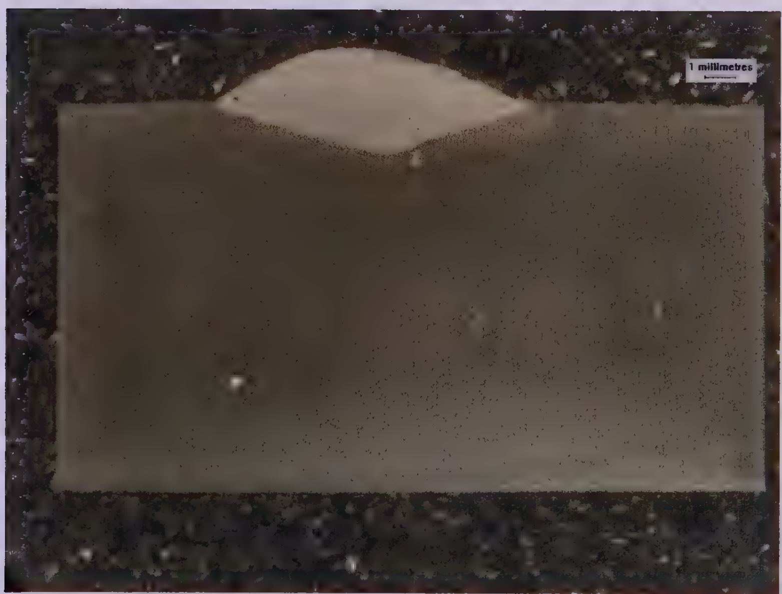

FIGURE 51. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Positive; Section 1.5″ from End of Weld (Test #22 – Long Arc)

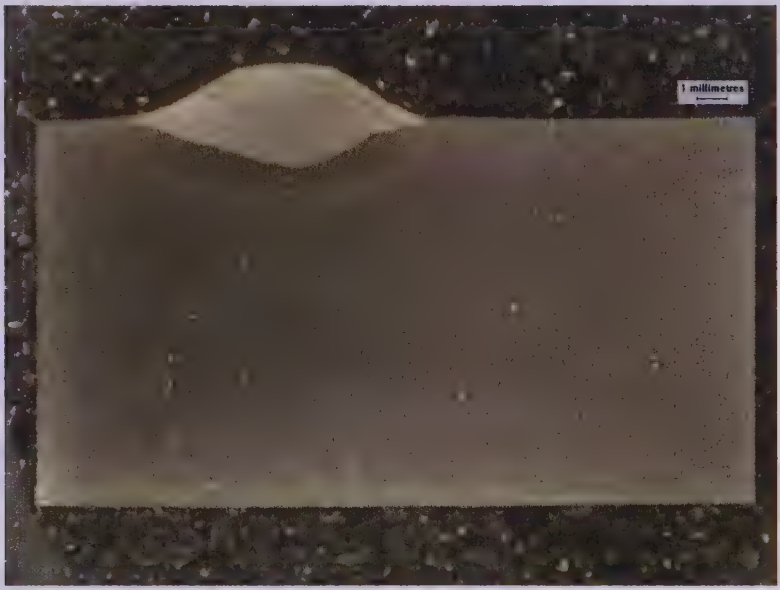

FIGURE 52. – Macrostructure of E7018 – 1 PLUS electrode on AC 50/50; Section 1.5" from Start of Weld (Test #23 – Long Arc)

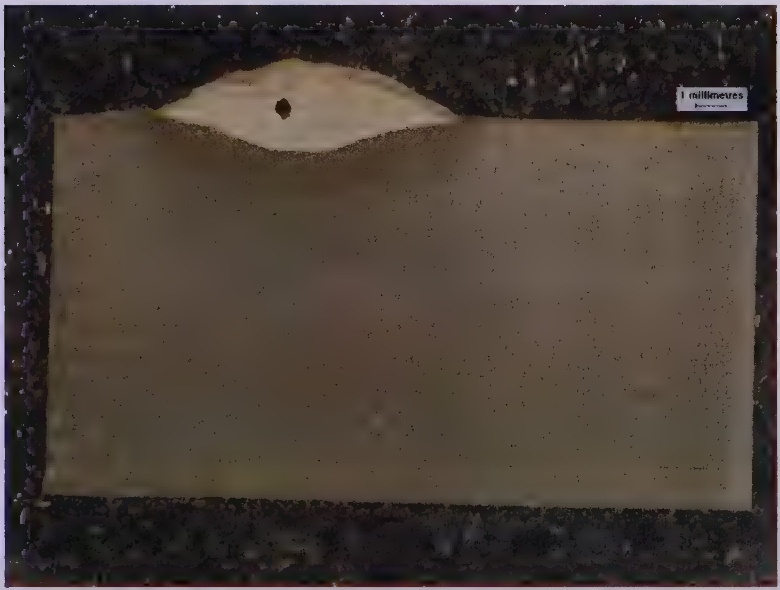

FIGURE 53. – Macrostructure of E7018 – 1 PLUS electrode on AC 50/50; Section 1.5" from End of Weld (Test #23 – Long Arc)

FIGURE 54. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Negative; Section 1.5″ from Start of Weld (Test #24 – Long Arc)

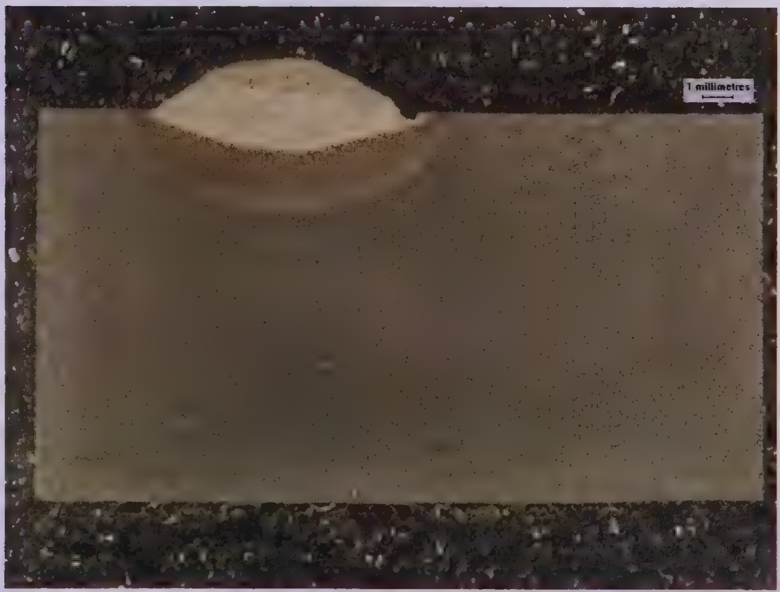

FIGURE 55. – Macrostructure of E7018 – 1 PLUS electrode on DC Electrode Negative; Section 1.5″ from End of Weld (Test #24 – Long Arc)